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THE STARK EFFECT FOR $H\beta$ AND *He* λ 4686

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ABSTRACT

Hβ.—Components of $H\beta$ under fine analysis are measured in various fields up to 47 kilovolts/cm. Theoretically unexpected components of this line are present in one of the analyses reproduced, and absent in another. From known variations in the character of the sources, and observations on helium mixed with the hydrogen, it is proved that the source which gave the spurious components was confused and that the applied field was not in the same direction for all atoms. Consequently the p and s components could not be separated completely. The most prominent of the doubtful components, $p \doteq 4$, are found to be due to the very strong components $s \doteq 4$. It is suggested that in the experiments by Stark the space charge may have been sufficient to cause a similar confusion.

He λ 4686.—At least three components of this line in fine analysis of the Stark effect are clear in an accompanying photograph. The observed spacings are 0.37 and 0.39 A, the calculated value being 0.33 A in each case. Further measurements are prevented by hydrogen band lines.

The main purpose of this note is to present experimental evidence in support of a suggested explanation of the appearance of certain components in Stark's[1] analysis of $H\beta$ which are questioned by the theory. To this is added a brief report of a partial fine analysis of the Stark effect for the ionized helium line λ 4686, which appeared on some of the plates taken during this investigation.

It is well known that Kramers[2] met with marked success in his application of Bohr's principle of correspondence to the explanation of the polarizations and relative intensities of components of the

[1] *Annalen der Physik*, **48**, 193, 1915.

[2] *D.K.D. Vidensk. Selsk, Skr. naturvidensk. og mathem. Afd.*, p. 8; *Rãekke*, **3**, 3, 1919.

Balmer lines observed by Stark in high electric fields. The agreement with the photographs of $H\gamma$ and $H\delta$ was especially good. On the other hand, real difficulties appear in the case of $H\beta$. A number of components recorded by Stark for this line are wholly unexpected. Also, it so happens that the estimated intensities for certain components of $H\beta$ show an unusual variation from the photographic densities measured by Stark.

In order to identify components due to Stark effect, it will be convenient to recall that according to the theory first given independently by Epstein[1] and by Schwarzchild,[2] a component of a Balmer line due to a transition $(m_1, m_2, m_3) \rightarrow (n_1, n_2, n_3)$ is displaced from the original line by an amount determined by

$$\Delta\nu = \frac{3hE}{8\pi me} Z ,$$

where E is the external electric field, and $Z = (m_1+m_2+m_3)(m_1-m_2) - (n_1+n_2+n_3)(n_1-n_2)$. Hence a component in the pattern of the group due to Stark effect may be identified by the corresponding value of Z.

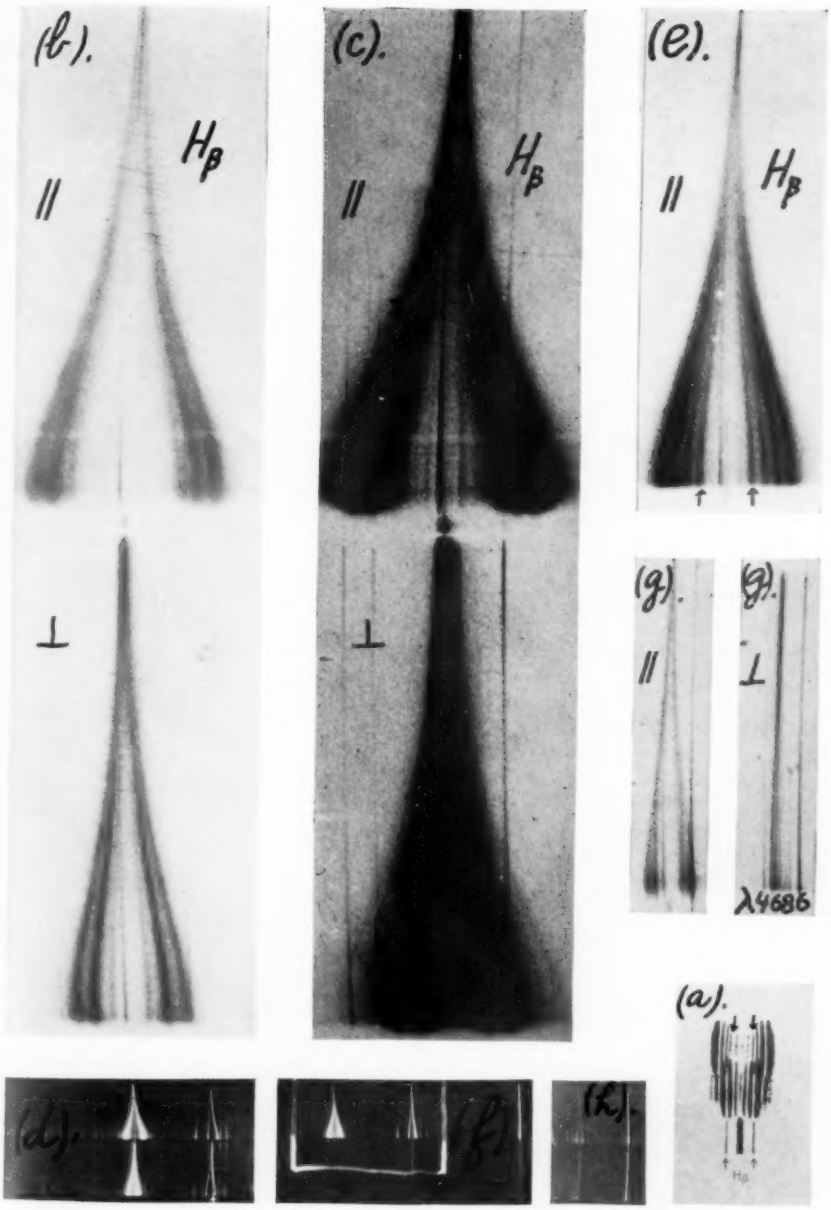
In his analysis of $H\beta$, Stark has recorded, without any expression of doubt, the parallel components for which $Z = \pm 4$ (i.e., $p:\pm 4$) and the undisplaced perpendicular components (s:0). Additionals components not expected on the theory are doubtfully placed at $p:\pm 12$ and $s:\pm 8$. These are shown, along with the theoretical expectations, in Figure 1, which is taken from the paper by Kramers. The lengths of the lines indicate the intensities; the numbers are the values of Z. The photograph of $H\beta$ published in the monograph by Stark[3] is reproduced in Plate IX*a*. It is to be expected that this remarkably clear reproduction of an excellent analysis of the Stark effect for $H\beta$ at 74 kv./cm will nevertheless be an imperfect representation of the components as they appeared on the original plate. The weakest components appear only after the strong components are so overexposed that a true reproduction of their relative densities cannot be given. The measures by Stark for densities of

[1] *Annalen der Physik*, 50, 489, 1916.

[2] *Ber. Akad. Berlin*, p. 548, 1916.

[3] *Elektrische Spektralanalyse chemischer Atome*, Leipzig, 1914.

PLATE IX



components of $H\beta$ in two field-strengths are reproduced in Table I, columns 1 and 2. The lines on either side of the undisplaced line mark the positions of Rowland ghosts due to $H\beta$. Arrows at the top of the figure point to the components $p:\pm 4$.

Considering the components in more detail, it is evident that $p:\pm 12$ are the most doubtful. They do not appear to have been photographed as entirely separate lines. Provided that the electric field is known to have been strictly constant, their presence is justly inferred from an asymmetrical broadening of the overexposed components $p:\pm 10$. It is useless to consider undisplaced components in absence of exact knowledge of experimental conditions. The real problem is to explain the presence of the components $p:\pm 4$, which are quite distinct in the photograph. It will be an added advantage if the explanation can deal satisfactorily with the doubtful components $s:\pm 8$.

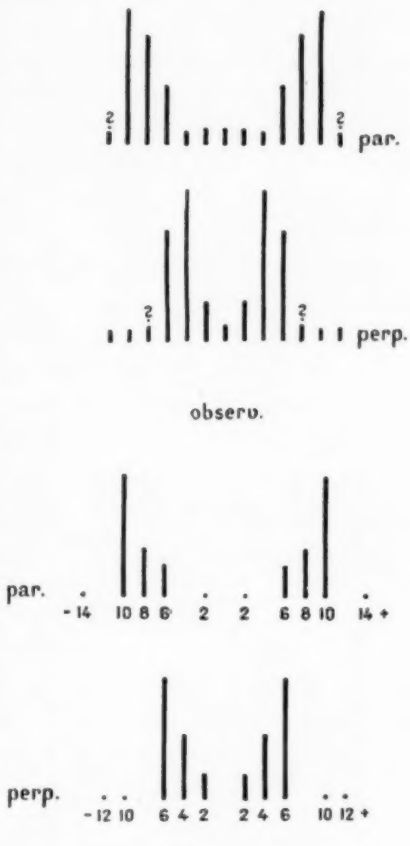


FIG. 1

Kramers suggests that possibly the components in question are Rowland ghosts. From the spacing between the original line and its ghosts, it is clear that ghosts of the components $p:\pm 10$ should be observable if present; and in view of the intensities of these components, their ghosts should appear as soon as any. As they are absent, the ghost theory fails. This has been pointed out by Stark. The present investigation has suggested an alternative explanation.

The experimental arrangement was identical with that described in an earlier paper.[1] A mixture of pure hydrogen and helium at a total pressure of 2 mm was contained in a vacuum system of large

TABLE I

Hβ IN ELECTRIC FIELD

PARALLEL COMPONENTS

Z	Density at 74 kv./cm	Density at 104 kv./cm	Δλ Due to Field Expressed in kv./cm				
			47.0	45.1	38.9	28.9	18.6
(12)	.....	(1)	.....	.....	.....	.....	.....
10	1.88	11.5	−7.00	−6.85	−5.86	−4.32	−2.89
8	1.73	9.1	−5.58	−5.41	−4.60	−3.46	−2.37
6	1.12	4.8	−4.22	−4.05	−3.42	.....	.....
(4)	(0.36)	(1)	.....	.....	.....	.....	.....
2	.16	1.2	−1.35	−1.32	−1.08	.....	.....
(0)	(.10)	(1.4)	.....	.....	.....	.....	.....
−2	.22	1.2	+1.45	+1.32	.....	.....	.....
(−4)	(0.26)	(1)	.....	.....	.....	.....	.....
−6	1.00	4.8	4.31	4.06	3.56	.....	.....
−8	1.40	9.1	5.78	5.48	4.76	3.53	2.35
−10	1.63	11.5	7.26	6.87	5.94	4.43	2.77
(−12)	.....	(1)	.....	.....	.....	.....	.....

PERPENDICULAR COMPONENTS

Z	Density at 74 kv./cm	Density at 104 kv./cm	Δλ Due to Field Expressed in kv./cm			
			47.5	42.0	37.9	28.4
+12	0.25	1	.....	−7.61	−6.73	−5.04
+10	0.45	1.1	−7.37	−6.41	−5.71	.....
(+ 8)	.....	(1.3)	.....	.....	.....	.....
+ 6	1.78	9.7	−4.36	−3.87	−3.46	−2.56
+ 4	2.03	12.6	−2.88	−2.54	−2.28	−1.67
+ 2	1.08	3.3	−1.46	−1.24	−1.14	−0.82
(0)	(0.62)	(1.4)	.....	.....	.....	.....
− 2	1.08	3.3	+1.39	+1.29	+1.12	.....
− 4	2.03	12.6	2.91	2.64	2.28	1.75
− 6	1.64	9.7	4.33	3.94	3.47	2.62
(− 8)	.....	(1.3)	.....	.....	.....	.....
−10	0.34	1.1	.....	6.58	.....	4.23
−12	0.27	1	.....	7.85	.....	5.10

capacity. A modified Lo Surdo tube served as the source. As usual, the light from near the cathode was passed through a double-image prism and focused on the slit of a glass-prism spectrograph having a dispersion of 5.6 A/mm at *Hβ*. The tube carried a current of

[1] *Physical Review*, 23, 667, 1924.

14 ma. when the applied voltage was 7 kv. Under these conditions, the light-intensity was satisfactory, all components being observed visually. Seed 30 plates were found to be sufficiently sensitive without staining. They were exposed one hour to obtain the lines reproduced in this paper.

Plate IX*b* and IX*c* are enlargements of the same photograph of $H\beta$, and were obtained by varying the time of exposure in printing. It was found impractical to reproduce a complete and clear analysis on a single print. Plate IX*c* is much overexposed for most components in order to show $s:\pm 10$, $s:\pm 12$, and $p:\pm 2$. Plate IX*d* is a contact print from the original plate. None of the doubtful components appear on this and other plates which show unmistakable evidence of the very weak components $s:\pm 10$, $s:\pm 12$. There is still no sign of $p:\pm 14$. The measurements of the observed displacements at various fields are recorded in Table I and plotted in Figure 2. The field strengths have been determined from the separations of the components $p:\pm 10$ and $s:\pm 6$ on the assumption that Epstein's theory is correct.

A great many secondary spectrum lines are present. They may be distinguished by their small Stark effects. The strong undisplaced line near the normal position of $H\beta$ occurs only in the flashes which are frequently seen in Lo Surdo tubes.

The helium present in the discharge has been found useful. Near $H\beta$ is the parhelium line group λ 4922. Of this group, the diffuse series line λ 4922 may be identified by its presence at zero field. For the present, it is important to note that in this analysis of λ 4922 there is no *p*-component of the same wave-length as the strongest *s*-component (marked with an arrow).

The new plates confirm the photographic densities assigned to the components at 104 kv./cm by Stark, but not accurately reproduced in his photograph (Plate IX*a*). It is necessary, of course, to distinguish between actual intensities of light and the densities of photographic impressions produced by the light. Only the densities have been measured. As a very rough estimate, the ratio of actual intensities $s:\pm 4$ to $s:\pm 6$ may be taken as 2. Kramers estimates this ratio to be 1 : 2, nearly. This variation of the theoretical estimate from the facts is of relatively small consequence in the theory. Since

$H\beta$ is associated with a transition involving very small quantum numbers, variations of this kind occasion no surprise.

At one time when the voltage on a different and somewhat aged

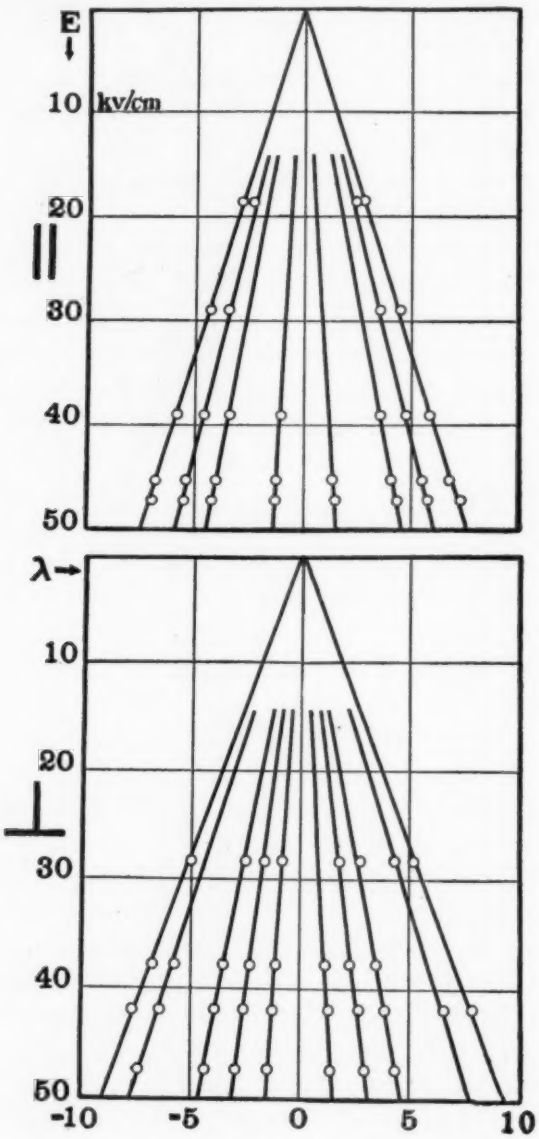


FIG. 2

tube was 6 kv. and the current 10 ma., the analysis of $H\beta$, examined with the aid of an eyepiece, was seen to be distinctly unusual. The components $p:\pm 4$ were undoubtedly present as well as an apparent p-component of *He* λ 4922 having the same wave-length as the strongest s-component to which attention has just been directed. A plate was therefore exposed for one hour. The result is shown in Plate IX*e;* contact print in Plate IX*f*. The s-components, though sharp, are very weak, due to loss by reflection. This fact needs a brief explanation. A crystalline quartz window, used on all tubes, rotated the plane of polarization through just 90°, so that the p-components appeared the stronger on the plate. A similar piece of quartz was commonly placed just in front of the "perpendicular" image on the slit; but it was not at hand when this photograph was taken.

The discharge, in this case, was of an unusual character. Normally a small pit is formed in the center of the exposed surface of the cathode. The positive ions therefore travel in a small beam along the axis of the tube. During the exposure just described, the pit formed was circular and indicated that the positive ions had formed a hollow cylinder or cone. That is, the center of the exposed cathode was not appreciably affected by their action.

It is clear that the energy which produced the spurious p-component of *He* λ 4922 really belonged to the strongest s-component of the same wave-length. In the opinion of the writer, this gives the key to the interpretation of other spurious components. In some Lo Surdo discharges[1] the external field may not be in the same direction in the case of all atoms. If such confusion exists, a double-image prism is unable to separate completely the p- and s-components. Corresponding to each very strong s-component there must appear on the plate a spurious p-component of the same wave-length and vice versa. This explanation probably holds for a canal-ray tube also, when the space charge due to a heavy current is appreciable. This emphasizes the importance of a check in experimental work of this kind, such as is afforded in this case by the analysis of *He* λ 4922.

This view receives support from the photograph of $H\beta$ published by Stark. The strongest components of all are $s:\pm 4$ of the same

[1] Only two plates out of twenty-five showed this effect.

wave-length as the spurious p-components which consistently appear in the published analyses. Also the components $p:\pm 8$ are sufficiently strong to account in a similar way for the presence of the doubtful components $s:\pm 8$. The present photographs show that no serious experimental departure from the expectations based on the correspondence principle occurs in the Stark effect for $H\beta$.

He λ 4686

For some time the Stark effect for the ionized helium line λ 4686 has been a matter of interest. In 1916 Evans and Croxson[1] attempted to test the theory of the origin of this line by its Stark effect. From the rough theory of this effect given by Bohr,[2] but two components were predicted for each line. The ratio of the separations $H\beta$:λ 4686 (calculated to be 3.47) would test the origin of λ 4686. They obtained a sufficiently strong field; but, according to the photograph which accompanies their note, they neglected to use a double-image prism. From what we now know, it is not surprising that they got only a broadening of the line, and could draw no very definite conclusions from their experiment.

In the following year Nyquist[3] obtained a rough analysis in a field of 38,600 v./cm. Two symmetrically placed p-components were noted with displacements ± 1.24 A. An undisplaced s-component was believed to be complex although it could not be resolved into a fine analysis. Nyquist observed that the ratio of the separations for $H\beta$:λ 4686 was 4.75. On the rough theory this was nearly $24/(3^2-2^2)$ instead of the predicted $24/(4^2-3^2)$, and presumably the conclusion was that the helium line might be due to a transition $3\rightarrow 2$ instead of $4\rightarrow 3$. It is very probable that Nyquist measured the centers of gravity of groups of components, and with this interpretation his measurements do not disagree with the more recent detailed theory by Epstein and Kramers.

Additional interest is now attached to this line because Kramers[4] believes it offers the best chance to trace experimentally the connections he has predicted between the fine structure and the Stark effect. Since some of the components of the Stark effect in fine

[1] *Philosophical Magazine*, **32**, 327, 1916.
[2] *Ibid.*, **27**, 506, 1914; **30**, 404, 1915.
[3] *Physical Review*, **10**, 226, 1917.
[4] *Zeitschrift für Physik*, **3**, 199, 1920.

analysis have been photographed, as described in the following paragraph, it seems possible that these important connections may be confirmed by experiments with specially designed optical apparatus now being assembled at this university.

The present analysis of this line in a maximum field of 46 kv./cm is shown in Plate IX*g;* contact print in Plate IX*h*. In the absence of a satisfactory comparison spectrum, no attempt has been made to measure a possible Doppler shift. Starting from the violet side of the *s*-components, we find three fine-analysis components, which are quite clear. Taken in the foregoing order, the separations are 0.39 A and 0.37 A at the maximum field. Theoretically each should be 0.33 A. The fourth line is possibly a fine-analysis component superimposed upon a band line which is undoubtedly present. The absence of any further components toward the red is a little puzzling. It may be that there is a Doppler shift of the order of 0.4 A, in which case the three certain components would be the central components expected on the theory. Doppler effects for this line will be investigated and reported later. If there is no appreciable Doppler effect, the component theoretically expected in the clear space between two band lines must be much weaker than its mate on the violet side.

Only one fine-analysis *p*-component can be distinguished. Using this as a guide in judging the position of its mate, a separation is obtained for the strongest *p*-components which is in excellent agreement with the theory by Epstein.

The photographs which form the basis of this note were taken at Yale University with the aid of a Fellowship from the National Research Council.

THE MACDONALD PHYSICS BUILDING
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SPECTROSCOPIC PHENOMENA OF THE HIGH-CURRENT ARC[1]

By ARTHUR S. KING

ABSTRACT

The high-current arc.—The direct-current arc carrying 1000 amperes or more at about 100 volts, usually between rods of small diameter, gave a source of great brilliancy and somewhat explosive character, producing mainly the spectrum of the neutral atom under conditions of high excitation.

Elements studied.—The spectra studied were those of *iron* from λ 2800 to λ 8400, and selected regions of *titanium, magnesium, calcium, copper,* and *aluminum.* Certain lines of *sodium, gallium, oxygen,* and *nitrogen* are also described.

Spectral characteristics of high-current arc.—The distinctive features are an intensification of the high-temperature lines, and a strong development of widening phenomena, with dissymmetries toward red or violet which often result in distinct shifts of the emission lines. *Reversals* are numerous, becoming less frequent with increasing wave-length, but extending into the infra-red of the iron spectrum. *Band spectra* are absent in emission but may appear in absorption. A *continuous spectrum* appears in the ultra-violet, resembling that of the condensed spark and of exploded wires. The high temperature and explosive action of the arc produced finely divided residues of iron and iron oxide which were examined microscopically.

Widening phenomena in the iron spectrum.—The degrees of widening, usually unsymmetrical, are given for 920 iron lines from λ 4250 to λ 8400. This material permits a selection of lines which remain stable in the ordinary arc and are suitable for wave-length standards. As the members of a multiplet show similar widening in the high-current arc, the selection of series groups is facilitated. *Energy level* is indicated by the degree of dissymmetry, lines of low level being nearly symmetrical, while the lines of multiplets starting from successively higher levels show increasing susceptibility to unsymmetrical widening. The type of widening shows a close relation to the temperature classification, and for the high-temperature lines the results supplement those of electric-furnace investigations.

Phenomena for other elements.—The other spectra studied showed effects similar to those of the iron spectrum. Exceptional intensity for an enhanced line was noted in the case of λ 4481 of *magnesium.* High-temperature arc lines of *magnesium* and *copper* showed very large red displacements. The D lines of *sodium* and other lines given by minimum excitation showed distinct red dissymmetry. The *oxygen* triplet λ 7772–λ 7776 and four *nitrogen* lines in the infra-red appear in the arc between iron electrodes.

Comparison of high-current arc with other sources.—A comparison of the tendency to displacement of iron lines in the high-current arc with that observed in the *pressure arc,* polar region of the *ordinary arc, tube arc, disruptive spark,* and *exploded wires* showed similar effects as to direction and relative magnitude in all of these sources.

It is generally recognized that each of our laboratory light-sources is especially adapted to the production of a certain type of spectral lines, and that in a given spectrum the response of various groups of lines to different degrees of excitation, beginning with several temperature stages of the electric furnace, can be traced

[1] *Contributions from the Mount Wilson Observatory,* No. 298.

through various forms of arcs and sparks, up to the most disruptive spark discharges. In the lower excitations, the spectrum of the neutral atom naturally predominates, the lines belonging to higher energy levels gradually developing, but in many metallic spectra the ionized atom begins to emit at the higher furnace temperatures, and the enhanced lines increase in strength as we pass through the scale of excitations until in the more powerful sparks the lines of the neutral atom have almost disappeared.

This paper records some observations of the spectrum of the metallic arc carrying a very large current, perhaps the most effective source thus far devised for developing the lines of the neutral atom and for showing their peculiarities of structure.

When the current of an arc that is normally operated for steady burning at about 5 amperes is increased to 20 or 30 amperes, no decided change in the spectrum results other than a general intensification and an increase in the number of reversed lines. The arc spreads over a larger area on each electrode, and there is little alteration in the character of the discharge. But if the current is increased to the order of 1000 amperes, there is no longer room on the small terminals for a normal spreading of the discharge. The electrodes are rapidly consumed, but as the arc must pass between the small areas at their ends, the current density is greatly increased and some features of the discharge, which in the low-current arc have little effect, are greatly intensified. It was with the object of observing the spectral changes brought about by such unusual arc conditions that the following experiments were carried out.

EXPERIMENTAL METHOD

Electrical power to the desired amount was available from a 500-kw. direct-current generator, with voltage regulation up to 150 volts. The current leads are the same as are regularly used, with the lower voltages of the dynamo, for the electric furnace, and the connection is made with the arc holders without introduction of any extra resistance. The arc terminals are held horizontally in clamps similar to those of the tube furnace.[1] These are water-cooled bronze blocks, with graphite bushings fitting around the electrodes. The

[1] *Mt. Wilson Contr.*, No. 247; *Astrophysical Journal*, **56**, 318, 1922.

bronze pieces slide on their supporting frame, the final connection to the dynamo leads being of flexible, water-cooled copper tubing.

The most suitable form of arc electrode for the metal in use, and also the most effective voltage, must be found by experiment. Most of the work thus far has been with iron terminals consisting of rods 4 mm in diameter inserted in the ends of 19-mm graphite rods and projecting initially about 5 cm beyond the graphite. These were used for a succession of the explosive arcs until they melted back to the graphite. Rods of magnesium, aluminum, copper, and calcium have been used in the same way. If the material is pulverized or will not make good electrical contact with the graphite, it may be held in small tubes of copper or other metal, which are inserted in the graphite rods. This method was used with powdered titanium.

The arc terminals are adjusted with the ends of the rods or tubes just touching, and the dynamo circuit is then closed. The arc is a blinding flash, and molten metal, much of it in very small droplets, is widely scattered. With a potential of 100 volts, the throw of the ammeter is usually to 1000 or 1100 amperes, but the full value of the current is evidently not recorded on account of the brief duration of the arc. It is hoped later to make detailed observations on the character of the discharge, but it is clearly a true arc and not a fusion of the rods by an overload of current, as the terminals shorten until a fairly definite gap is left, depending on the voltage, about 3 cm with 100 volts, and the arc breaks, leaving the remaining portions of the rods intact.

Iron rods having diameters larger and smaller than 4 mm have been tried with less satisfactory results. Apparently, for terminals of any given material, a size must be used that will confine the arc to a small area at the ends and still enable the rod to carry the current for the short time required, permitting the arc to pass without melting down the rods as a whole.

Carbons 19 mm in diameter loaded with the material to be vaporized were tried with several metals. The arc is then started by sliding the clamps to bring the carbons into contact, and a steady-burning, though greatly overloaded, arc can be maintained for some time by pushing the carbons together as they burn away. The carbons quickly become white hot up to the clamps. The spectro-

scopic features of the arc when thus controlled will be described later. The explosive character is diminished, and strong vaporization of the carbon takes place. It is feasible to interrupt and re-ignite this arc by directing an air blast intermittently at the gap. The strong ionization between the terminals causes the arc to spring again when the blast is turned off.

The residues from the arc when made to discharge between 4-mm iron rods gave evidence of the high temperature prevailing through a large mass of the material. In addition to the large amount of iron turned into vapor, much more was just below the vapor state. As the arc with 100 volts normally burned to a gap of at least 32 mm before breaking, about 0.4 cc of iron was melted in the time occupied by the brief flash. The high temperature prevailing gave extreme fluidity to the portion of the iron not actually vaporized. Droplets, about 0.5 mm in diameter, caught on bits of glass, after a flight through some 2 m of air, retained sufficient heat to sink into the glass. Still more striking was the large amount of highly tenuous oxide. After the flash of the arc, a large volume of yellow smoke arose, and when this was dissipated, hundreds of filaments of iron oxide were seen floating in the air. These were usually several centimeters long, and were apparently formed in the wake of flying globules, the residue of which often remained as a black droplet at the end of the mass. My brother, L. M. King, made a microscopic examination which showed the highly divided state of the iron resulting from the high temperature and the explosive action of the arc. Magnifying powers up to 1000 diameters revealed a very beautiful structure consisting of fine yellow strands of oxide. These strands, of surprisingly uniform thickness, were more or less meshed together, and at intervals along them could be seen very tiny globules of iron, still in the black state. Micrometer measurements, under a power of 500 diameters, gave the size of the droplets and the thickness of the yellow strands. For a specimen whose total length was 2.3 mm, the droplet at the head measured 0.09 mm; the black globules along the strands were all close to 0.0018 mm diameter, while the strands themselves were only 0.0008 mm thick. The production, in a fraction of a second, of large quantities of such firmly divided matter, in addition to the larger drops of liquid iron

expelled from the arc, gives some idea of the difference between this source and the quietly burning arc carrying a current of a few amperes.

PHOTOGRAPHY OF THE SPECTRUM

The spectrograms for the most part were made with the 15-ft. concave grating spectrograph, the second order, with a scale of 1.86 A per millimeter, being used for wave-lengths shorter than λ5500, while the bright first order was employed for the red end of the spectrum.

As far as the brightness of the spectra and the sensitiveness of the plates permitted, spectrograms were made with a single flash of the arc. For the first order of the grating, a single flash gave fully exposed spectra as far as λ5800, and two flashes to λ6700. The much weaker second order required ten flashes in the green, while for the infra-red of the first order, photographed on dicyanin-bathed plates, as many as twenty-three flashes were made. The terminals were usually so arranged that the light near the negative pole, as it burned backward, fell on the slit, as this radiation was found to have the maximum effect in bringing out peculiarities of the line structure.

SPECTROSCOPIC FEATURES

The high-current arc gives, in the main, the spectrum of the neutral atom, and is characterized by three distinctive features in which it supplements the spectroscopic sources regularly in use. These are, first, an intensification of the high-temperature lines; second, an absence of the band spectrum of the metal or compound except as it may appear in absorption if a favorable background is present; third, the development in very high degree of any peculiarities of widening, especially dissymmetry toward red or violet, to which the individual lines are subject. The manner in which these effects result from the observed characteristics of the arc may now be considered.

High-temperature lines.—The physical phenomena involved in the action of the high-current arc, consisting of rapid melting of the electrodes, extreme fluidity of the molten matter, the production of a large volume of vapor, and the intense brightness of the radiation, are indications of the way in which the 100 kw or more of electrical

energy are being used up. Evidently we have between the poles a considerable volume of dense vapor, subject to excitation conditions which in the ordinary arc are transient, if present at all. The low-current arc between metallic electrodes or loaded carbons is maintained in a steady state by a moderate vaporization from small areas on the electrodes; but there are moments of unusual activity during which intensely heated vapor is ejected from the poles, giving, especially in the core of the arc, a strong luminosity in which the high-temperature or "core" lines are prominent. The spectrum indicates that these conditions, transient in the ordinary arc, are the prevailing state of the high-current arc. The radiation from this central mass of vapor dominates the spectrum, and gives it the appearance of being made up of high-temperature lines. The low-temperature lines, being emitted largely by the envelope of cooler vapor, are relatively inconspicuous. The lines of Class I, the most prominent lines of the furnace spectrum, are notably narrow and weak in the high-current arc, as though practically absent from the hot central portion. Class II lines, which are the strongest group in the ordinary arc, are evidently emitted as wide lines by the central portion, but undergo very wide self-reversal, owing to their persistence in the cooler envelope. It is the strong emission of lines of Classes III, IV, and V that especially distinguishes the high-current arc. Their intensity indicates that in the scale of excitation this source is fully active at the stage where the furnace is weak and the low-current arc only moderately effective.

Band spectra.—The absence of the bands from spectrograms of the high-current arc is probably due to the short exposures required for the line spectrum emitted by the central vapor, and is a further step in the process which gives relative weakness to the low-temperature lines. With the iron arc, for instance, there is no question that large quantities of oxide are formed, but the envelope in which the combination takes place is apparently forced out some distance by the explosive action of the arc, and, as a result, is of relatively low density. The time required to photograph the line spectrum of the inner vapor is thus too short for the band emission to be registered. That a band spectrum is present was shown clearly in the aluminum spectrum by the band structure appearing in absorption on a back-

ground formed by broad, enhanced lines of the metal. To study the band spectrum in emission would require relatively long exposures of the arc envelope away from the region of intense line emission. The absence of bands permits an undisturbed study of the line spectrum, which, in regions such as the orange and red of iron and titanium, is highly advantageous.

Line dissymmetry.—In view of the very extensive data which have been accumulated in several lines of investigation, it seems necessary to admit that actual displacements of lines of certain types are produced in several sources of high excitation. In the ordinary arc, the unsymmetrical widening of some lines, usually toward the red, is a very familiar phenomenon; but spectroscopists have concerned themselves chiefly with the possible effect of this broadening upon wave-length measures, and the normal position of a line is established for conditions of the source in which the dissymmetry is a minimum. But when under certain conditions a line wings out strongly, say to the red, with nothing corresponding on the violet side of the normal position, it is evident that a certain proportion of the radiation is tending toward the production of a line displaced to the red. If in any source this proportion is increased, so that the radiation in question becomes dominant, the result is a line whose maximum is shifted to the red of the normal position. This happens in the high-current arc, in very different degrees for different types of lines, but so generally that lines which attain any considerable strength and show no tendency to displacement are rare. While this arc, partly because it produces high-temperature lines with great intensity, shows the displacing action more generally and with greater distinctness than any other source which has been used for spectroscopic work, other forms of electrical discharge give effects which are qualitatively similar. These will be discussed in connection with the data for the iron spectrum.

The results of a preliminary survey of high-current arc effects for several elements will now be presented. Spectrograms over an extended region were made only for iron. The effect upon individual lines will be given for part of the region, not only for direct application to problems concerning the iron spectrum, but as an example

of what we may expect for the spectra of the high-current arc in general.

IRON

Continuous spectrum.—The high-current arc with iron terminals gave a continuous ground of considerable strength, beginning about λ 4300 and extending into the ultra-violet. This is noteworthy as being similar to that given by certain high-potential discharges. The spark spectra of several metals are known to show strong continuous radiation in the ultra-violet, and it is a feature especially noted by Anderson[1] and by Smith[2] in their studies of wire explosions, when these were confined in a wooden block.

Ultra-violet spectrum.—In the ultra-violet, at least as far as λ 2800, it is evident that the low-temperature iron lines, selected on the basis of the writer's investigation of the furnace spectrum,[3] are produced chiefly in an envelope outside of the region of intense excitation between the poles. They appear as absorption lines on the continuous ground noted above, with little evidence of emission wings. The continuous spectrum can be weakened by using plates of greater contrast, and then these lines are seen to have wings much narrower in proportion to the width of the reversal than those of lines of the same temperature classes in the visible spectrum. Interspersed among the low-temperature absorption lines are the higher-temperature lines in various stages of sharpness and narrow reversal, the latter usually unsymmetrical; but the outstanding emission lines in this region are the enhanced lines. These can be selected at a glance, being strong and yet not reversed. It is known that the enhanced lines of iron in the ultra-violet are relatively easy of production in the ordinary arc. The emission in the interior of the high-current arc consists mainly of these and of the high-temperature arc lines.

Visible spectrum.—The continuous spectrum holds out to about λ 4300 with sufficient strength to be disturbing when the discharge near the negative electrode is favored, and as the dissymmetry of

[1] *Mt. Wilson Contr.*, No. 178; *Astrophysical Journal*, **51**, 37, 1920.

[2] *Mt. Wilson Contr.*, No. 285; *Astrophysical Journal*, **61**, 186, 1925.

[3] *Mt. Wilson Contr.*, No. 247; *Astrophysical Journal*, **56**, 318, 1922.

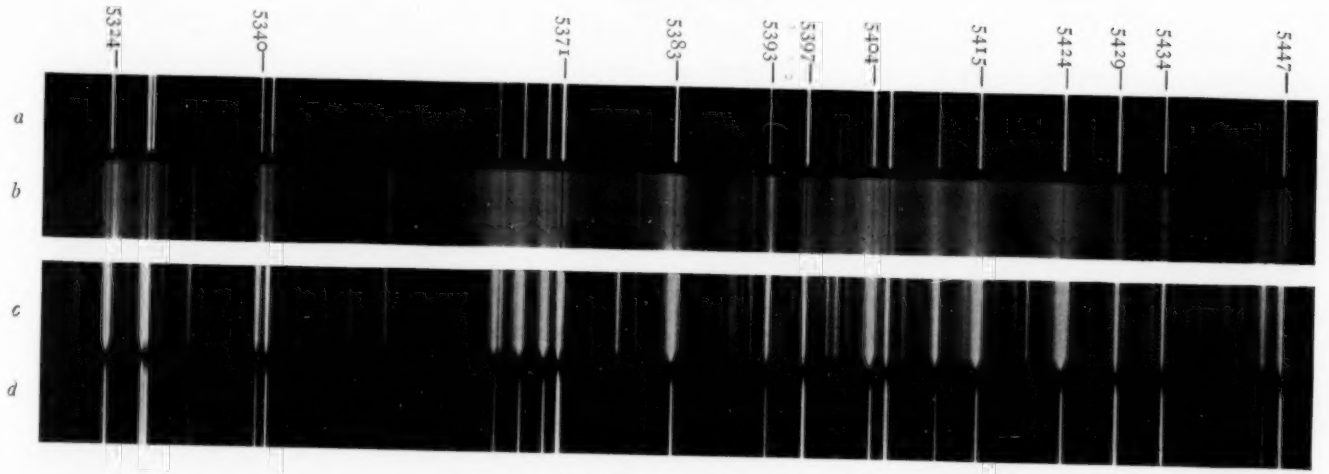
line structure is most marked in this portion of the arc, Table I, with its description of individual lines, begins at λ 4250. From this limit into the infra-red, we have well-defined lines, and no bands; and the absorption of the cooler vapor results in self-reversal, throughout the visible spectrum, of a large proportion of the lines. The reversals, however, decrease in breadth, taking up normally but a fraction of the total width of the emission line. This lessened effectiveness of the cooler envelope corresponds with the relative scarcity of low-temperature furnace lines at the red end of the iron spectrum. In the infra-red, practically the entire radiation of the arc appears to come from the region of highest excitation.

The enhanced lines of the visible region, which can be obtained at the poles of the ordinary arc, are present in the high-current arc, but show only moderate intensity. The distinguishing feature is a very rich spectrum of the neutral atom, with an intensification of high-temperature lines which are weak in other sources.

Reversals.—In the ordinary arc, with currents below 10 amperes, seven lines to the red of λ 4250 may be expected to reverse. When higher currents within the range of the usual arc apparatus are used, the reversals increase in number and the stronger low-temperature lines up to λ 5500 may be obtained in reversal. In contrast with this condition, the high-current arc gives 176 reversals beyond λ 4250, or about one line in five. While the reversals become less common with increasing wave-length, they are frequent as far as λ 6678, and even λ 7511 was reversed. High-temperature lines, including some of those most difficult of production in the furnace, undergo reversal, if fairly strong and not extremely diffuse. Examples are the Class V lines in the green-yellow consisting of λλ 5383, 5404, 5415, 5424, and similar neighboring lines. These have a considerable degree of diffuseness, with widening toward the violet, but are clearly reversed in the high-current arc (see Plate X).

Intensification of high-temperature lines without notable widening.—Plate X also shows a phenomenon observed in the earlier work when the arc was formed between iron and carbon rods 19 mm in diameter, the former being used as a positive terminal. This arc would burn steadily for some seconds and was not nearly so bright as the explosive arc between small iron rods. The lower concentra-

PLATE X



ARC SPECTRUM OF IRON

a, *d*, low-current arc
b, high-current arc
c, high-current arc, iron-carbon, large electrodes

tion of energy prevented any pronounced widening of the lines; at the same time the arc retained the power to give great intensity to the high-temperature lines. Comparison of its spectrum, Plate X*c*, with that of the ordinary iron arc in Plate X shows that the low-temperature lines are of equal strength in the two sources, while the high-temperature lines are strengthened in the high-current arc about in proportion to their temperature class, lines of Class V being the strongest in the region illustrated.

Widening phenomena.—Table I contains 920 lines, having widening characteristics as follows:

Unsymmetrically widened toward red	397
Unsymmetrically widened toward violet	62
Widened without clear dissymmetry	175
Sharp or symmetrically reversed	276
Uncertain on account of blends	10

About 43 per cent of the total number thus show distinct dissymmetry toward the red. These lines differ in appearance from widened lines of the ordinary arc, where we have a shading-off from the position of the normal maximum. In the high-current arc, the maximum has moved into this region of shading. Unreversed lines, when fairly narrow, appear displaced with reference to the comparison lines of the ordinary arc. The stronger lines, except in the infra-red, are almost invariably reversed, the reversal being more or less on the violet edge of the line in the high-current arc, but coinciding closely with the position of the regular arc line. The displacing effect is probably very general, and under higher dispersion many lines classed as "sharp" in Table I, and some of these which appear simply widened, would probably show a slight red dissymmetry. This was indicated by photographs of two sections of the iron spectrum, one in the blue, the other in the green-yellow, taken in the second order of the 30-ft. plane-grating spectrograph, with a scale about double that of the concave grating. The freedom from astigmatism made it possible to obtain a record of the very intense radiation near the negative electrode. Under these conditions, apparently no line remained perfectly symmetrical.

Lines widened toward the violet occur in groups, notably near λλ 5100, 5400, 5700, and 6050. They are high-temperature lines,

and very few have been obtained with the furnace. The outstanding exception is the Class I line, λ 5110.414, which is narrowly reversed, with the violet side clearly stronger. In the furnace spectrum[1] this line has remarkable strength at low temperature, the only comparable lines being λλ 5166.288 and 5168.904, which are disturbed by adjacent lines in the high-current arc, and may have similar dissymmetry.

Widening without dissymmetry occurs to a small degree for many lines which are sharp in the ordinary arc. Lines which become diffuse are uniformly high-temperature lines. In extreme cases of diffuse widening, the line structure disappears in the high-current arc, which probably accounts for the fact that many faint iron lines measured by Kayser[2] do not appear on my photographs.

Use in wave-length measurements.—The exaggeration in the high-current arc spectrum of any peculiarities of structure present in a more or less incipient state in the ordinary arc shows at once the lines that should not be used as wave-length standards, and also the degree in which other lines may be useful. It may be safely assumed that lines which show only slight widening or dissymmetry in the high-current arc will show very little wave-length variation in the regular laboratory arc, especially if care is taken as to what part of the arc is observed.[3] Thus lines marked S, Ro, Ru_1, u_1, or w_1 may be expected to remain fairly stable. Lines whose dissymmetry is u_3 or u_4 are totally unreliable, while u_2 lines should be discarded unless of very moderate strength. The higher degrees of symmetrical widening, denoted by w_3, w_4, w_5, belong to lines which are more or less diffuse in the regular arc and offer difficulty in setting on their centers.

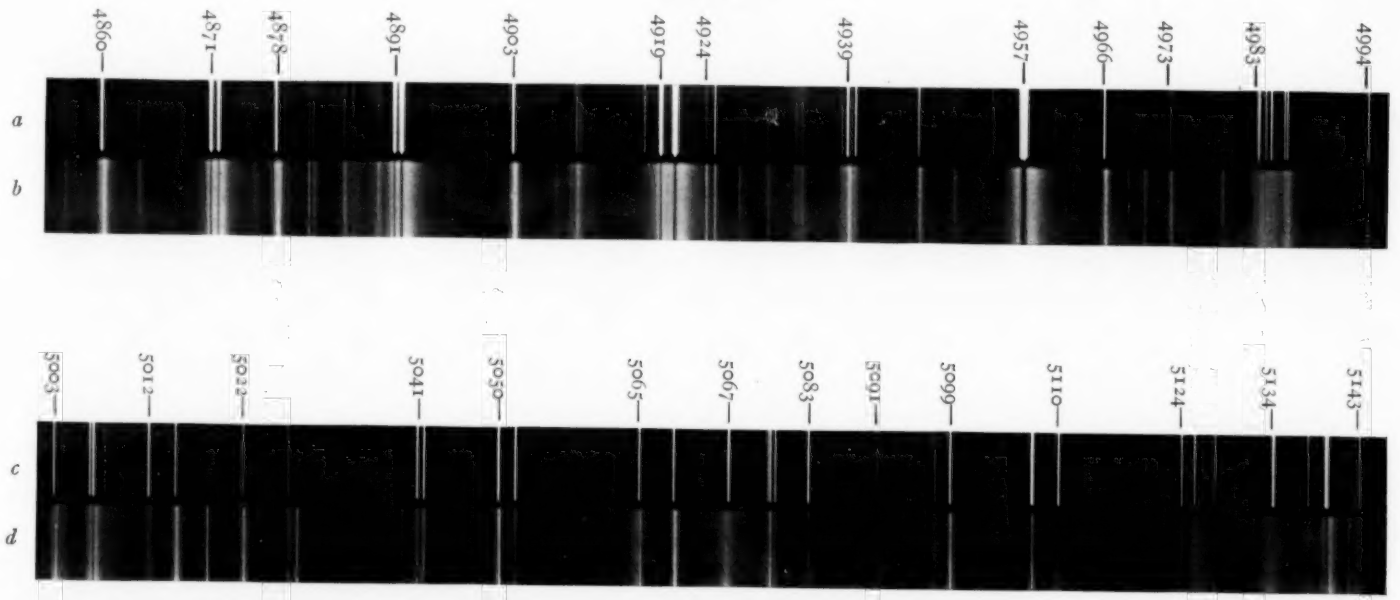
There is no certain evidence that the high-current arc reveals any new iron lines. The existing tables for the iron arc were sufficient for the identification of almost all lines not to be ascribed to impurities. This would indicate that the neutral atom emits a definitely limited number of lines, that these lines are present, though often

[1] *Mt. Wilson Contr.*, No. 66; *Astrophysical Journal*, **37**, 239, 1913.

[2] *Handbuch der Spektroscopie*, **6**, 896.

[3] See St. John and Babcock, *Mt. Wilson Contr.*, No. 137; *Astrophysical Journal*, **46**, 138, 1917.

PLATE XI



ARC SPECTRUM OF IRON

a, *c*, low-current arc
b, *d*, high-current arc

very faint, in the arc with moderate current, and that the chief characteristic of the high-current arc in this respect is an intensification of such faint lines when they arise from the higher energy levels of the atom.

EXPLANATION OF TABLE I

Wave-lengths.—The wave-lengths are chiefly those of Burns[1] on the international system. A few faint lines are from the lists of Kayser[2] and of Meggers and Kiess.[3] These are indicated by an asterisk or a dagger, respectively.

Symbols.—The symbols used to describe the lines in the high-current arc are as follows:

Ro. A nearly symmetrical reversal; probably never perfectly symmetrical. (See p. 246)

S. A narrow line without distinct dissymmetry; if the line is faint, a slight one-sidedness may not show.

Ru_1. A clear dissymmetry of reversal with the red side stronger. The dissymmetry increases up to Ru_4, in which case the absorption line is at the violet edge of the emission line. Partial reversal is indicated by r.

u_1 to u_5. Increasing degrees of widening toward the red without reversal.

u_1v, etc. Dissymmetry toward the violet in varying degrees. If reversed, the absorption line is to the red of the emission maximum.

w_1 to w_5. Increasing degrees of widening without clear dissymmetry.

Remarks.—These are at the end of Table I and are referred to by numbers adjacent to the wave-lengths.

[1] *Lick Observatory Bulletin*, **8**, 27 (No. 247), 1913.

[2] *Handbuch der Spektroscopie*, **6**, 896.

[3] *Bulletin of the Bureau of Standards*, **14**, 637, 1919.

TABLE I

Widening Characteristics of Iron Lines in High-Current Arc

λ	Type	λ	Type	λ	Type	λ	Type
4250.134	Ru3	4389.251	S	4529.684	S	4687.394	w1
4250.791[1]	Ru1?	4390.460	u1	4531.155	Ru1	4688.208	w4
4258.386	Ru1	4390.957	u1	4531.642[17]	S	4689.497	w1
4258.611	u1	4395.288	u1	4537.684	S	4690.145	w2
4258.950	u1	4401.304[8]	u3?	4542.422	w1	4691.416	w1
4259.988[2]	R	4401.447[8]	S?	4547.027	S	4700.201[28]	?
4260.135[2]	R	4404.752	Ru1	4547.855	ru3	4701.051	w3
4260.489	Ru3	4407.716	Ru3	4549.477[18]	w1	4704.955	u3
4264.208	w4	4408.420	Ru2	4550.824	w3	4705.460	S
4265.256	w4	4409.121	S	4552.551	S	4707.287	ru3
4266.068	ru3	4415.127	Ru1	4554.467	w2	4707.485[29]	?
4267.831	Ru3	4422.570	Ru1	4555.904[19]	w2	4708.972	w1
4268.752	ru3	4423.145	w1	4556.128	w2	4709.091	w4
4271.171	Ru3	4427.313	Ru1	4556.941	w1	4710.283	w1
4271.764[3]	Ru1?	4430.197	S	4558.110	S	4711.478[29]	u3
4276.670	w4	4430.622	Ru2	4560.114	u3	4712.104	w1
4278.128	w4	4432.575	S	4564.832	S	4714.182	w1
4279.872	u1	4433.222	w4	4565.324	w1	4721.000	S
4280.5*	w3	4433.808	w3	4565.684	u3	4727.410	u2
4282.406	Ro	4435.154	w1	4566.525	S	4728.549	w2
4285.448	ru3	4436.931	S	4566.990	S	4729.016	S
4288.150	S	4438.355	u3	4568.789	S	4731.488	w2
4288.962	S	4439.886	S	4568.842[20]	u1	4733.594	w1
4290.384	w1	4442.349	Ru2	4574.240	u3	4734.101	S
4290.869	w1	4442.838	S	4574.730	S	4735.844	w1
4291.472	Ru1	4443.199	Ru1	4579.344	S	4736.788	Ru2
4292.293	w1	4445.426	S	4579.825	S	4740.344	S
4294.132[4]	Ru1	4446.853	w2	4580.602	u2	4741.533	w1
4298.043	ru1	4447.137	S	4581.529	u3	4745.804[21]	w4
4299.254	Ru4	4447.727	Ru2	4583.843[21]	w1	4757.581	S
4302.191	S	4450.324	S	4584.732[22]	w3	4768.334[22]	w2?
4304.548	S	4454.387	Ru1	4584.826[22]		4768.397[22]	w2?
4305.458	ru1	4456.335	S	4587.136	S	4771.703	w1
4307.910	Ru1	4459.125	Ru2	4592.658	ru1	4772.818	w1
4309.041	S	4461.205	w1	4595.368	S	4776.075	w1
4309.382	Ru2	4461.658	Ru1	4596.062	u3V	4779.438	S
4315.092[5]	Ru1	4462.011[9]	u3	4598.138	u3	4785.963	w2
4321.798	S	4464.773	w1	4600.939	S	4786.810	w1
4325.770	Ru1	4466.557	Ro	4602.009	w1	4788.761	S
4326.762	S	4469.390	Ru4	4602.946	Ru1	4789.655	ru1
4327.100	ru1	4472.713	w1	4607.665	u3	4791.250	S
4327.92*	u1	4476.023[10]	Ru1?	4611.290	ru3	4798.269	w2
4330.962	S	4476.082[10]	u4	4613.217	u3	4798.736	S
4337.052	Ru1	4479.608	S	4614.214	w2	4799.412	S
4338.270	u1	4480.143	w1	4615.568[23]	u3	4799.891	w2
4343.278	u1	4481.621	u2	4618.763	S	4800.652	w1
4343.704	u1	4482.176[11]	Ro?	4619.295	u2	4802.887	S
4346.561	u1	4482.262	Ru1	4625.061	u3	4804.529	S
4347.239	S	4482.750	u1	4629.327	w1	4807.729	w2
4347.854	u4	4484.238	ru3	4630.128	w1	4808.155	S
4348.946	S	4485.674	w3	4632.919	w1	4809.14	S
4351.553	w1	4488.134	w2	4635.853	S	4809.94	S
4352.740[6]	Ru1	4488.920	u2	4637.522	u3	4811.04	S
4358.506	u1	4489.744[12]	Ru1	4638.020	u3	4813.11	S
4360.813	S	4490.088	S	4643.467	u3V	4817.784	S
4365.902	S	4490.768	w4	4647.440	ru1	4824.162	S
4367.584	ru1	4494.571	Ru2	4654.502	w1	4832.732	S
4367.910	u1	4502.592	S	4654.637	u3	4834.511	S
4369.777	Ru1	4504.846	u3	4657.598	w1	4835.866	w4
4372.994	S	4508.287[13]	w2	4661.539[24]	w2	4838.519	u3
4373.568	S	4514.190	S	4661.978	S	4839.546	S
4374.495	S	4515.337[14]	w2	4663.185	w1	4843.156	u2
4375.934	Ru1	4517.530	S	4667.460[25]	rw2	4844.016	S
4376.782	u1	4520.238[15]	w1	4668.153	ru3	4845.656	S
4377.796	S	4522.530	S	4669.184	u3	4848.898	w1
4382.777[7]	S	4522.636[16]	w1	4673.171	w2	4855.688	u3
4383.548	Ru1	4523.399	w1	4678.856[26]	rw2	4859.757	Ru2
4384.682	S	4525.154	Ru2	4679.229[27]	?	4863.655	u2
4385.260	u2	4526.567	S	4680.302	S	4871.333	Ru2
4387.809	u2	4527.796	S	4680.475	w1	4872.154	Ru2
4388.422	ru4	4528.624	Ru2	4683.566	w1	4878.226	Ru2

TABLE I—*Continued*

λ	Type	λ	Type	λ	Type	λ	Type
4881.722	S	5079.228	ru_2	5283.634	Ru_4	5539.28*	S
4882.168	u_3	5079.742	ru_1	5288.533	S	5543.184	u_2v
4885.443	u_3	5080.3*	w_1	5293.973	S	5543.951	u_3
4886.342	w_5	5083.344	ru_1	5298.789	S	5546.512	u_2v
4888.651	w_2	5090.787[42]	w_4	5302.315	Ru_4	5547.00*	u_2
4889.021	S?	5096.992	u_4v	5307.362	S	5549.9*	S
4889.13*	u_2	5098.594[43]	?	5316.620[52]	w_1	5553.586[58]	w_2?
4890.770	Ru_3	5098.706	ru_2	5322.049	S	5554.879	u_2v
4891.510	Ru_3	5099.07*	u_2	5324.196	Ru_3	5557.954	w_3
4903.325	Ru_3	5107.454[44]	Ro?	5326.154	S	5560.230	w_4
4907.745	u_3	5107.645[44]	Ro?	5328.044	Ro	5562.712[56]	w_2?
4909.397	u_3	5110.414[45]	Ru_1v	5328.539	Ru_1	5563.609	u_2
4910.032	u_3	5121.646	w_4	5330.000	w_1	5565.703	u_4v
4919.008	Ru_3	5123.727	ru_1	5332.673	w_1	5567.401	S
4920.521	Ru_3	5125.137	u_4	5332.906	u_1	5569.631	Ru_4
4923.92[24]*	w_1	5127.364	ru_1	5339.949	Ru_4	5572.857	Ru_4
4924.775	w_1	5129.63*	u_3	5341.031	Ru_1	5576.106	Ru_4
4927.42*	S	5131.477	u_1	5353.386	u_2	5584.768	S
4927.875	w_4	5133.676	Ru_4v	5362.744	u_2v	5586.772	Ru_4
4930.331	u_2	5136.09*	u_2	5364.859	Ru_4v	5594.661	u_2v
4933.348	w_2	5137.394	w_4	5365.403	ro	5598.306	u_4v
4934.023	w_3	5139.269	Ru_3	5367.455	Ru_4v	5600.242	u_2
4938.183	w_3	5139.481	Ru_3	5369.960	Ru_4v	5602.905	ru_2
4938.828	Ru_3	5141.750	u_1	5371.496	Ro	5615.663	Ru_4
4939.689	u_1	5142.540	w_5	5373.704	u_2v	5618.646	u_3
4940.401	u_2	5142.934	Ru_1	5379.578	S	5624.563	ru_4
4950.121	u_2	5148.061[46]	?	5383.366	Ru_4v	5633.970	u_5
4952.646[25]	w_1	5148.260	w_3	5389.463	w_5	5636.708	S
4957.311	Ru_3	5150.845	ru_1	5391.643	u_2	5638.278	u_3
4957.612	Ru_3	5151.916	ru_1	5393.185	Ru_4	5641.464	u_3
4966.104	u_3	5159.066	w_4	5397.135	Ro	5643.99	w_1
4967.890	u_4v	5162.312	u_2	5398.285	w_5	5649.66	S
4968.709	S	5165.432	u_4	5400.504	u_4v	5652.32	u_4
4969.942	w_4	5166.288	Ro	5404.131	Ru_4v	5655.179[57]	w_2?
4970.496	S	5167.492	Ro	5405.780	Rø	5655.506	u_3
4973.112	u_3	5168.904[47]	Ro?	5410.900	Ru_4v	5658.542[58]	w_2?
4978.614	u_3	5169.020[48]	w_1	5415.189	Ru_4v	5658.836	u_4
4982.524[26]	ru_4	5171.601[49]	Ru_1	5424.057	Ru_4v	5660.70*	S
4983.274[26]	ru_4	5187.922	u_2	5429.701	Ro	5661.36*	S
4983.858[26]	ru_4	5191.475	Ru_4	5434.527	Ro	5662.533	u_3
4985.267	u_3	5192.364	Ru_4	5436.594	S	5667.533	u_4v
4985.562	u_2	5194.950	Ru_1	5445.040	u_4v	5679.023	u_4v
4988.970	u_4	5195.472	w_5	5446.922	Ro	5680.26*	S
4991.288	u_4	5198.717	ru_2	5455.435	u_4v	5686.532	u_4v
4994.133	ru_1	5202.342	Ru_2	5455.617	Ro	5691.509	u_3
5001.881	Ru_3	5204.585	w_1	5462.964[52]	u_4v	5693.638	u_2v
5002.815	u_3	5208.610	Ru_4	5463.27[52]	u_4v?	5698.05*	S
5005.729	Ru_3	5215.195	Ru_4	5464.286	w_2	5698.37*	S
5006.134[27]	Ru_3?	5216.277	Ru_1	5466.417	w_5	5700.26*	S
5007.31[23][a]	w_2?	5217.405	Ru_4	5466.993	S	5701.555	S
5012.073[28]	Ru_1	5225.533	S	5472.720	u_2	5702.4*	S
5014.960	ru_2	5226.876	Ru_4	5473.913	u_2	5705.988	u_4v
5018.437[29]	S	5227.187	Ru_1	5476.296	S	5707.068	w_1
5022.255	u_2	5229.86*	Ru_4	5476.582	u_2	5709.395	u_4
5027.144	u_4	5232.954	Ru_2	5480.872	u_2	5711.867[59]	w_2?
5027.212	S	5235.392	u_2	5481.252	u_2	5712.150[59]	w_2?
5028.135	S	5236.189	w_1	5483.111	u_2	5714.155	S
5029.623	S	5242.495	ru_2	5487.783[53]	u_5	5715.107	u_4
5039.266	u_2	5243.798	w_2	5493.508	w_4	5717.848	u_4
5040.902	w_3	5247.052	S	5494.468	S	5720.8*	S
5041.079	Ru_1	5250.212	S	5497.521[54]	Ru_1	5731.775	u_4
5041 763	Ru_1	5250.650	ru_2	5501.471[54]	Ru_1	5738.3*	S
5044 24*	u_2	5251.971	S	5503.08	u_5	5741.861	u_4
5048 454	u_2	5253.479	u_2	5506.785[54]	Ru_1	5747.95	u_3v
5049.830	Ru_2	5254.956	S	5512.277	u_4	5752.035	u_3v
5051.643	Ru_1	5263.321	ru_4	5519.56*	u_4v	5753.145	u_4
5054.65*	S	5263.874	S	5521.1*	S	5754.41	S
5065.016	u_4v	5266.569	Ru_4	5522.46	u_2	5756.78[60]	w_2?
5065.201	S	5269.538	Ro	5525.552	u_2	5760.351	S
5067.162[26]	w_4	5270.357	Ru_1	5529.15*	S	5762.434	S
5068.784[41]	ru_4	5273.178[50]	u_2?	5532.752	S	5763.015	u_4
5074.750	u_4v	5273.379[50]	u_2?	5535.423	S	5775.095	u_4
5079.002	u_4v	5281.804	Ru_4	5537.71*	S	5778.47	S

TABLE I—*Continued*

λ	Type	λ	Type	λ	Type	λ	Type
5780.621[61]	S?	6082.718	S	6496.462[76]	w_8	6875.98	w_1
5780.83[61]	u_4	6085.267	w_1	6498.950	S	6880.65	u_4
5782.15	S	6089.567	S	6501.681	S	6881.6*	w_8
5784.69[68]	S?	6096.689	u_4	6509.56	w_1	6885.77	u_4
5785.29	u_4	6102.185	u_4V	6516.08	w_8	6898.31	u_4
5791.044	u_4	6103.196[79]	u_4V?	6518.380	u_3	6902.80	u_4
5793.932	u_4	6116.25	w_1	6528.53	w_1	6911.52	S
5798.194	u_4	6127.919	S	6533.97	u_5	6916.710	u_4
5804.06	u_4	6136.624	Ru_1	6546.251	ru_1	6930.64	u_3
5804.45[63]*	S?	6137.704	Ru_1	6569.233	u_3	6933.632	S
5806.727	u_5V	6141.74[73]*	u_4	6574.238	S	6945.215	S
5809.249	u_4	6147.85	S	6575.028	S	6947.501	u_3
5811.93	S	6151.630	S	6581.22	w_1	6951.278	u_5
5814.80	u_4	6157.733	S	6591.32	u_3	6960.334	w_1
5816.36	S	6163.560	S	6592.928	ru_1	6971.95	w_1
5828.48	u_5V	6165.370	S	6593.881	S	6975.46	u_5
5834.05	S	6170.499	u_4V	6597.607	u_3	6976.934	S
5835.8*	u_4V	6173.346	S	6608.03	S	6977.445	S
5837.709	S	6180.216	w_1	6609.124	S	6978.864	S
5838.4*	u_4	6188.037	u_4	6609.56	w_8	6988.541	w_1
5848.09*	u_4V	6191.568	Ru_1	6625.04	S	6999.928	u_4
5849.6*	S	6200.322	S	6627.563	u_4	7000.633	S
5852.19*	u_4V	6213.440	S	6633.77[27]	u_5	7008.014	u_4
5856.084	w_1	6215.151	w_1	6639.7[73]	u_3	7010.362	S
5857.134[64]	u_3?	6219.290	S	6646.98	S	7011.364	S
5859.20[68]	u_3?	6226.77	u_3	6653.88[79]	u_3	7014.99†	S
5859.612[69]	u_3?	6227.259	S	6663.26[80]	S?	7016.075	S
5862.351	u_4V	6229.234	S	6663.452[80]	S	7016.436	u_4
5864.2*	S	6230.732	Ru_1	6678.001	ru_1	7023.003	u_4
5873.211	u_3	6232.667	u_4	6699.14	u_3	7024.084	S
5883.842	u_3	6240.3*	w_8	6703.570	S	7024.649[83]	u_5V?
5891.9*	S	6240.652	S	6705.139[81]	w_8	7027.60	S
5892.71*	u_3	6246.344	u_4	6710.31	S	7038.271	u_4
5902.52	S	6252.567	ru_1	6713.14	u_3	7044.60[84]†	w_8
5905.677	u_4V	6254.266	S	6713.76	w_8	7067.44	S
5906.0[66]*	u_3?	6255.955	w_1	6715.410	u_4	7068.422	S
5909.99*	u_3	6256.371	S	6716.24	S	7071.88	u_4
5914.16[67]	u_3V?	6265.145	S	6717.556	u_3	7083.396[85]	u_5V
5916.250	S	6270.229	S	6725.39	u_4	7086.76	u_4
5927.798[67]	u_5?	6280.622	S	6726.668	w_8	7090.417	u_4
5929.7[68]*	?	6283.05[74]	u_4	6732.06	S	7095.447	u_4
5930.177[69]	u_3V?	6290.968[74]	w_4	6733.171	u_4	7107.486	S
5934.679	u_3	6297.803	S	6739.54	S	7112.182	w_1
5940.972	u_4	6301.524	u_4	6745.11	S	7130.956	u_4
5949.35	u_4	6302.512	u_4	6750.163	S	7132.999	S
5952.749	u_3	6311.506	S	6752.734	u_4	7142.522	u_5
5956.700	S	6315.317	S	6755.609	S	7145.317	u_4
5958.2*	S	6315.814	S	6777.44	w_8	7151.495	S
5959.9*	w_1	6318.027	S	6783.71	w_8	7155.64	u_5
5962.1*	u_3	6322.696	S	6786.88	u_4	7158.502	u_5
5969.8*	w_8	6330.86[78]	u_3?	6793.26	w_1	7164.480	u_4
5975.350	S	6335.341	S	6796.11	w_1	7175.937	u_5
5976.803	u_4	6336.844	u_4	6804.020[82]	S?	7180.020	S
5983.708	u_4	6344.159	S	6804.27[82]	S	7181.22	u_4
5984.809	u_3V	6355.038	u_5	6806.859	S	7187.349	u_4
5987.061	u_3V	6358.684	S	6810.28	w_4	7189.17	S
5997.808	u_4	6362.889	S	6820.43†	w_8	7207.123	w_1
6003.038	u_4	6364.717	u_3?	6828.614	u_4	7207.430	u_4
6005.15	S	6380.751	S	6833.24	w_4	7219.698	w_1
6007.965	u_4V	6393.609	ru_1	6837.00†	S	7221.22[86]	u_4?
6008.583	u_4	6400.021	Ru_4	6838.86	u_4	7223.678	w_1
6020.06[70]}	w_4	6408.044	u_4	6839.828	S	7228.820	S
6020.177[70]}		6411.674	u_4	6841.362	u_4	7239.904	u_4
6024.062[71]	w_4?	6419.988	u_4	6842.668	w_8	7244.86[86]	u_5V?
6027.061	S	6421.361	ru_1	6843.685	u_4	7254.649	S
6034.1*	u_3	6430.859	ru_1	6854.82	S	7261.54[87]	w_4?
6035.5*	S	6436.43	S	6855.183	u_4	7284.853	S
6042.085	u_3V	6456.39	w_1	6857.25	S	7288.782	u_4
6055.991	u_4V	6462.737	S	6858.173	u_4	7293.093	u_4
6062.89	S	6469.216	u_3	6860.29	S	7306.61	u_5
6065.496	ru_1	6475.635	S	6861.93	S	7307.957	S
6078.482	u_4V	6481.881	S	6862.481	w_8	7311.112	u_4
6079.02	w_4	6494.993	Ru_1	6875.45	w_1	7320.72	u_5

TABLE I—*Continued*

λ	Type	λ	Type	λ	Type	λ	Type
7351.56[66]	u_8?	7454.02	S	7568.932	u_4	7832.243	u_4
7353.528[85]	u_4?	7461.534	S	7573.53†	u_4	7937.182	u_4
7375.57	u_4	7473.56†	w_4	7583.803	S	7941.09†	S
7382.99	w_3	7476.30†	w_4	7586.060	u_4	7945.889	u_4
7386.402	u_5	7482.00†	w_3	7617.93[50]	S	7994.48†	S
7389.432	u_4	7491.678	u_4	7620.531	u_4	7998.98	u_4
7401.707	S	7495.099	u_4	7650.82[20]	S	8028.37	u_4
7411.196	u_4	7498.56	S	7653.80†	u_4	8046.088	u_4
7418.680	S	7507.31	u_4	7661.24	u_4	8085.220	u_4
7421.60†	w_4	7511.059	ru_4	7664.303[91]	S	8220.42	u_4
7430.73[88]†	S	7531.181	u_4	7710.40	u_4	8327.080	w_3
7440.98[89]	w_5?	7546.173	S	7723.20†	S	8332.01	u_4
7443.022	S	7559.68†	w_4	7748.289	S	8387.785	w_3
7445.783	u_4	7563.03†	w_3	7780.594	u_4		

NOTES TO TABLE I

1. Blend with λ 4250.134.
2. These lines reverse, but structure is concealed by λ 4260.489.
3. Blend with λ 4271.171.
4. Dissymmetry very small.
5. Dissymmetry very small.
6. Small dissymmetry. Cf. λλ 4282, 4315.
7. In wing of λ 4383.548, sometimes as absorption line.
8. Blend.
9. Line has sharp center, may be two lines superposed.
10. Disturbed by λ 4476.082.
10a. Measured by Babcock by interferometer in Pfund arc, under standard conditions. Greatly intensified in high-current arc.
11. Blend with λ 4482.262.
12. Very narrow.
13–16. Enhanced lines.
17. Shading on red side may be caused by faint adjacent line.
18, 19. Enhanced lines.
20. Blend with λ 4568.789.
21. Enhanced line.
22. Blend.
23. Very faint.
24. Enhanced line, very faint.
25. Unusual case of diffuse line symmetrically reversed.
26. Similar to λ 4667.460, but has slight red dissymmetry.
27. Blend with λ 4678.856.
28. Disappears. Diffuse in ordinary arc.
29. Concealed by λ 4707.287.
30. Very faint.
31. Diffuse shading on red side may indicate presence of another line.
32. Blend.
33. Blend with λ 4889.13.
34. Enhanced line.
35. Very faint.
36. Three lines run together.
37. Blend with 5005.729. Degree of widening uncertain.
37a. In wing of 5006.134. Probably very diffuse.
38. Nearly symmetrical.
39. Enhanced line.
40. Very faint.
41. Reversal at violet edge of line.
42. Slightly shaded to red.
43. Blend with λ 5098.594.
44. Blend. Structure of lines somewhat uncertain.
45. Violet side of reversal slightly stronger.
46. Blend with λ 5148.260.
47. Blend with λ 5169.029.
48. Enhanced line.
49. Dissymmetry very small.
50. Blend.
51. Enhanced line.
52. Blend.
53. Wide shading to red.
54. Slight but distinct dissymmetry.
55. In shading of λ 5554.879.
56. Close to strong line λ 5563.609.
57. Blend with λ 5655.506.

NOTES—*Continued*

58. Blend with λ 5658.836.
59. Blend.
60. May be u_4v.
61. Blend.
62. Close to λ 5785.29.
63. In shading of λ 5804.06.
64. Uniform shading to λ 5859.20.
65. Blend.
66. Blend with λ 5905.677.
67. Difficult. May be faint companion on violet side.
67*a*. Uniform shading to λ 5929.7.
68. Blend with λ 5930.177.
69. Shading affected by λ 5929.7.
70. Blend. λ 6020.177 may widen to violet.
71. May widen to violet.
72. Disturbed by λ 6102.185.
73. May be *Ba*.
74. Shades into a second very diffuse line to red.
74*a*. May widen to violet.
75. Barely visible.
76. Shades into λ 6494.993.
77. Probably double. In ordinary arc sharp line appears superposed on very hazy line.
78. May be double. Measured by writer.
79. Shading may be affected by *Ba* line.
80. Blend.
81. Some shading to red.
82. Blend.
83. Blend with λ 7024.084.
84. May be shaded to violet.
85. Extremely hazy.
86. Very faint lines.
87. Line to violet seems to come up in high-current arc.
88. Hazy line appears on red side.
89. Disappears
90. Measured by writer.
91. Close to potassium line.

WIDENING EFFECTS AND ENERGY LEVELS

The work of Walters[1] and of Laporte[2] on regularities in the iron arc spectrum makes possible a comparison between widening effects and atomic energy levels. This is given in Table II, the notation of Walters being used, in which A is the lowest of a succession of levels. Lines of smallest dissymmetry in the high-current arc from λ 2800 to λ 8400 belong to multiplets starting from levels A, B, and C. The initial level, rather than the range of levels, is evidently the important feature. Thus a multiplet having a jump from A to M retains the Ro character of the smaller intervals which start from the A level. Jumps of B to R and C to Q have lines similar to multiplets with jumps between levels close together. An increased susceptibility to unsymmetrical widening is very distinct, however, for higher initial levels. Multiplets from level A are the most symmetrical, the A to E group consisting of sharp lines in the green in furnace Class I A, while the remaining nine multiplets include strong low-

[1] *Journal of the Optical Society of America and Review of Scientific Instruments*, **8**, 245, 1924.

[2] *Zeitschrift für Physik*, **23**, 135; **26**, 1, 1924.

temperature lines in the ultra-violet with minimum dissymmetry. Multiplets from levels B and C are also made up of low-temperature lines, and when their structure is clearly brought out, show, in general, a slight red dissymmetry. The D multiplets are an intermediate group, some consisting of faint red lines which remain sharp, perhaps because of low intensity, but two multiplets in the blue and green have lines of pronounced ru_2 structure. The prevailing temperature class of D multiplets is III. Starting from level F and high levels, we have the high-temperature lines of Classes IV and V, showing the very general widening toward the red indicated by u_3 and u_4. It is

TABLE II

ENERGY LEVELS OF IRON MULTIPLETS

Initial Level	Prevailing Type	Number of Multiplets
A	Ro	10
B	Ru_1	13
C	Ru_1	9
D	ru_2	5
F	u_3	2
G	u_3	1
J	u_4	1
K	u_4	1
K_1	u_4	1
L	u_4	1
M	u_4	1

noteworthy that none of the lines having dissymmetry toward the violet have as yet been arranged in multiplets. From their furnace behavior, it is evident that they are high-level lines, probably with unusual combinations.

Apparently the large electronic orbits giving rise to lines of high energy level are especially susceptible to disturbance by strong excitation, and the peculiarities of structure brought out by the high-current arc, especially for lines beyond the reach of the furnace, may be used to indicate energy level and thus supplement the temperature classification.

RELATION TO TEMPERATURE CLASSES

Slightly over one-third of the lines included in Table I have been classified in furnace spectra, the two most numerous types and the

two next in number being given in Table III for each temperature class. The data show a sharp or symmetrical structure prevailing for lines of Class I A, small dissymmetries in Classes I and II, and an increasing proportion of strongly widened lines in the higher classes. The considerable proportion of scattered types under Classes III, IV, and V is made up chiefly of faint arc lines which have not appeared in the low-temperature furnace, perhaps partly on account of the general faintness of such furnace spectrograms. Some of these lines remain sharp in the high-current arc, which is the typical behavior of low-temperature lines when unreversed. Whether they are really low-temperature lines will be clear when their multiplet connections with other lines are worked out. Other minor variations from a close correspondence are also found. Thus a low-level multiplet given by Laporte includes the lines λλ 4376, 4427, 4461, which were shown by the writer[1] to persist at temperatures as low as 1400°C. In the high-current arc these lines, while relatively weak, show a distinctly one-sided reversal. In the same region, λλ 4282, 4315, 4352, which Laporte places by themselves in a multiplet of uncertain level, are much more nearly symmetrical, but require higher temperature. They fade rapidly below 2000°C., and are placed in Class III in the revised list. In general, however, the correspondence with temperature class is close, and an examination of the ultra-violet shows the same relation holding in that region.

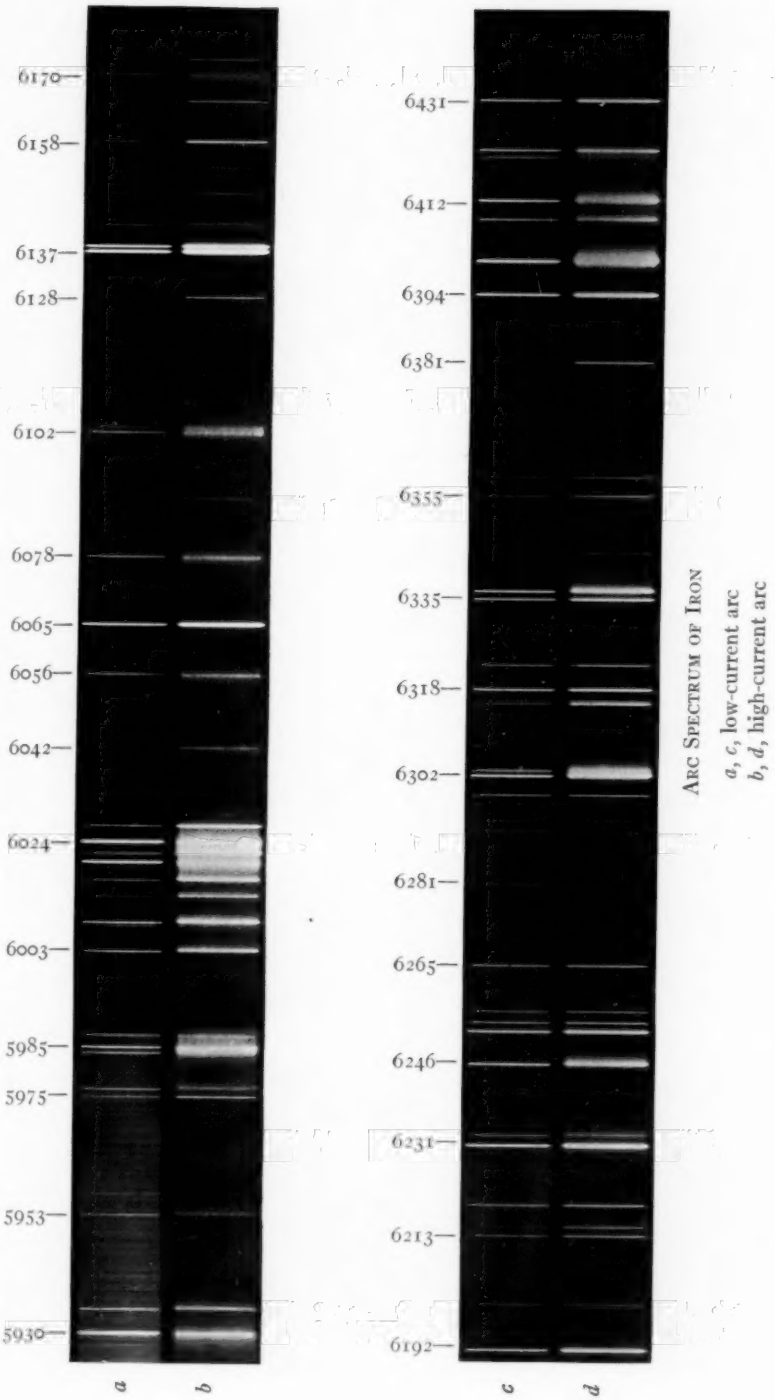
COMPARISON WITH OTHER LIGHT-SOURCES

1. *Pressure arc.*—In their study of the spectrum of the iron arc under high pressure, Gale and Adams[2] arranged the lines in groups according to the amount of pressure shift and tendency to widen unsymmetrically under pressure. This grouping has been taken into account in the later wave-length measurements of the iron spectrum, as the tendency of lines from the more intense regions of the ordinary arc to give divergent wave-length values was found to correspond closely with their behavior in the pressure arc. Since the high-current arc exaggerates a displacing action which is present in some degree in the ordinary arc, we may expect to find phenomena which

[1] *Mt. Wilson Contr.*, No. 247; *Astrophysical Journal*, **56**, 318, 1922.

[2] *Mt. Wilson Contr.*, No. 58; *Astrophysical Journal*, **35**, 10, 1912.

PLATE XII



ARC SPECTRUM OF IRON

a, *c*, low-current arc
b, *d*, high-current arc

follow closely those of the pressure arc. A comparison of widening effects with pressure displacements for 111 iron lines measured by Gale and Adams in the region covered by Table I is given in Table IV.

Table IV shows that the lines of groups *a* and *b*, with small or

TABLE III

RELATIVE NUMBER OF TYPES OF IRON LINES FOUND IN EACH TEMPERATURE CLASS, λ 4250–λ 7200

	IA	I	II	III	IV	V
Most numerous types	Ro, S	u_1, u_2	u_1, u_2	u_1, u_2	u_3, u_4	u_3, u_4
	9	22	19	29	39	86
Types next in number	u_1	Ro, S	Ro, S	u_3, u_4	u_1, u_2	w_3, w_4
	4	11	4	20	20	11
Number of lines of other types	1	1	2	14	25	15

moderate pressure shift, have at most only slight dissymmetry in the high-current arc. Lines which become strongly unsymmetrical under pressure are in group *c*, and those with extreme widening toward the red in group *d*. This gradation is followed closely in the high-current arc, where lines having widening indicated by u_3 and

TABLE IV

COMPARISON OF GROUPING OF IRON LINES IN THE PRESSURE ARC AND IN THE HIGH-CURRENT ARC

TYPE IN H.C. ARC	PRESSURE GROUP			
	a	*b*	*c*	*d*
S	2	14	.....	.....
Ro	9	2	.....	.....
u_1	13	30	.....	.....
u_2	.....	.....	8	.....
u_3	.....	.....	12	5
u_4	.....	.....	.....	16

u_4 predominate in the groups *c* and *d*, respectively. There is no case of real discordance, in which a line shows large effect for one source and small effect for the other. Evidently, by a slight adjustment of the two classification systems, lines can be assigned to the groups of Gale and Adams by examination of the high-current arc spectrograms, with the advantage that practically all the lines of the neutral atom can be treated by this method.

2. *Polar displacements in the ordinary arc.*—In their study of pole effect in the iron arc, St. John and Babcock[1] made use of the pressure groups in classifying the shifts which they measured between lines produced at the pole and in the center of the arc. The larger shifts to the red measured in this way fall into pressure groups *c* and *d*, while displacements to the violet are placed in a fifth group, *e*. In Table I of the present paper, 156 *c* and *d* lines occur, and of these 138 show large dissymmetry to the red in the high-current arc; the structure of the remaining lines is uncertain. All of the 44 lines of group *e* common to the two lists spread to the violet in the high-current arc. The one-to-one correspondence thus indicated supports the view that the polar conditions of the ordinary arc, much intensified, are the dominant conditions of the high-current arc.

3. *Tube arc.*—In this source,[2] a graphite tube containing a metal or salt is intensely heated and made to burn apart, thus forming an arc in vacuum at about 30 volts, with currents comparable with those used in the present investigation. The line dissymmetries observed correspond fully in direction and relative magnitude with those of the high-current arc in air. The tube arc, being a vacuum source, gives narrower lines than the arc in air, a feature which brings out the structure better for some strong lines, but is disadvantageous for the weaker lines, which are too narrow for classification.

4. *Disruptive spark.*—A comparison of the iron lines of a strongly condensed spark with those of the tube arc[3] has shown that the widening phenomena are of quite the same character. As the volume of vapor in the spark is small, only certain types of lines are wide enough to be satisfactorily grouped on the basis of widening, but many very strong arc lines in the ultra-violet are so reduced in intensity that the strong displacing action of the spark discharge, which was studied by microphotometer curves, shows very clearly.

5. *Exploded wires.*—The absorption spectra obtained when

[1] *Mt. Wilson Contr.*, No. 106; *Astrophysical Journal*, **42**, 231, 1915.

[2] *Mt. Wilson Contr.*, Nos. 73, 103; *Astrophysical Journal*, **38**, 315, 1913; **41**, 373, 1915.

[3] *Mt. Wilson Contr.*, No. 103; *Astrophysical Journal*, **41**, 373, 1915.

metal wires inclosed in a wooden block are exploded by a condenser discharge have been described by Anderson.[1] After these results were published, Anderson made a series of photographs of the iron spectrum with the same dispersion that I have used for the high-current arc spectra, and he has kindly placed this material at my disposal for comparison. The absorption lines given by the explosions show the same sort of widening or one-sided shading as appears in the high-current arc. Only the more pronounced effects are shown distinctly by the absorption lines, but evidently a displacing action is present, affecting the absorbing vapor in a way corresponding to that which in the high-current arc causes widening or displacement of the emission lines.

Six light-sources have thus been extensively investigated in this laboratory, in which the iron lines are affected in the same way. Superficially considered, these sources have little in common. The conditions vary from low arc voltages to high spark potentials, from a partial vacuum to pressures of many atmospheres, from the slight vaporization present in the spark to the large mass of vapor quickly produced in the high-current arc. Except in the case of the pressure arc, a high electrical excitation is evidently present in each source, but this is not necessary for displacements under high pressure. The tube furnace under pressure,[2] heated to moderate temperatures, has been shown to give line shifts fully as large as those of the pressure arc.

The material at disposal indicates that spectral lines possess an inherent sensitiveness to displacement toward the red or the violet (or in both directions in the case of diffuse lines), which increases for lines of high energy level. There is a possibility that agencies quite different in character may act upon the electron orbits in such a way as to produce the observed disturbances of period.

OTHER ELEMENTS

Titanium.—The spectrum was obtained best with pulverized titanium carbide contained in small copper tubes held in the ends of graphite rods. One flash of the very brilliant arc gave a strong spec-

[1] *Mt. Wilson Contr.*, No. 178; *Astrophysical Journal*, **51**, 37, 1920.

[2] *Mt. Wilson Contr.*, Nos. 53, 60; *Astrophysical Journal*, **34**, 37, 1911; **35**, 183, 1912.

trum for the region λ 4950–λ 6600. The symmetrical structure of the low-temperature lines and the varying degrees of dissymmetry toward the red for those of higher temperature showed that a grouping of lines as distinct as that for iron can be made. The band spectrum, usually very disturbing in this region, was quite absent in emission, but appeared in absorption in several places where the shading of diffuse lines furnished a background.

Calcium.—Varying amounts of the metal were used in the arc, the impurity in ordinary carbons being sufficient to show the structure of the stronger lines. Thin-walled graphite tubes of 4-mm bore containing the metal, supported in graphite rods, gave a large quantity of calcium vapor with little disturbance from the carbon. The spectrum is notable for the violet dissymmetry of many of the low-temperature lines. This was noted for H and K in the tube arc[1] and a similar reversal, with the violet side distinctly stronger, appears in the high-current arc in air. In the spectrum of the neutral atom the lines of the low-temperature sextet λλ 4283–4319 reverse with violet dissymmetry, as do the lines in the group λλ 4425–4435–4455. When λ 4227 is sufficiently weak, a slight dissymmetry with the red side stronger may be seen. Red dissymmetry which is more or less pronounced in the ordinary arc for the triplets with violet members at λλ 3949, 4093, 4578, and the single lines λ 4355, 4527, is intensified to such an extent that the lines almost disappear.

The pole effect as measured by Whitney[2] shows agreement with the foregoing dissymmetries as to direction and relative amount except in the case of H and K, for which the small red displacement (0.002 A) observed at the pole is perhaps within the errors of measurement for lines of this kind. The pressure displacements given by L. F. Miller[3] are also in agreement with the high-current arc data, except for a negligible pressure effect for H and K.

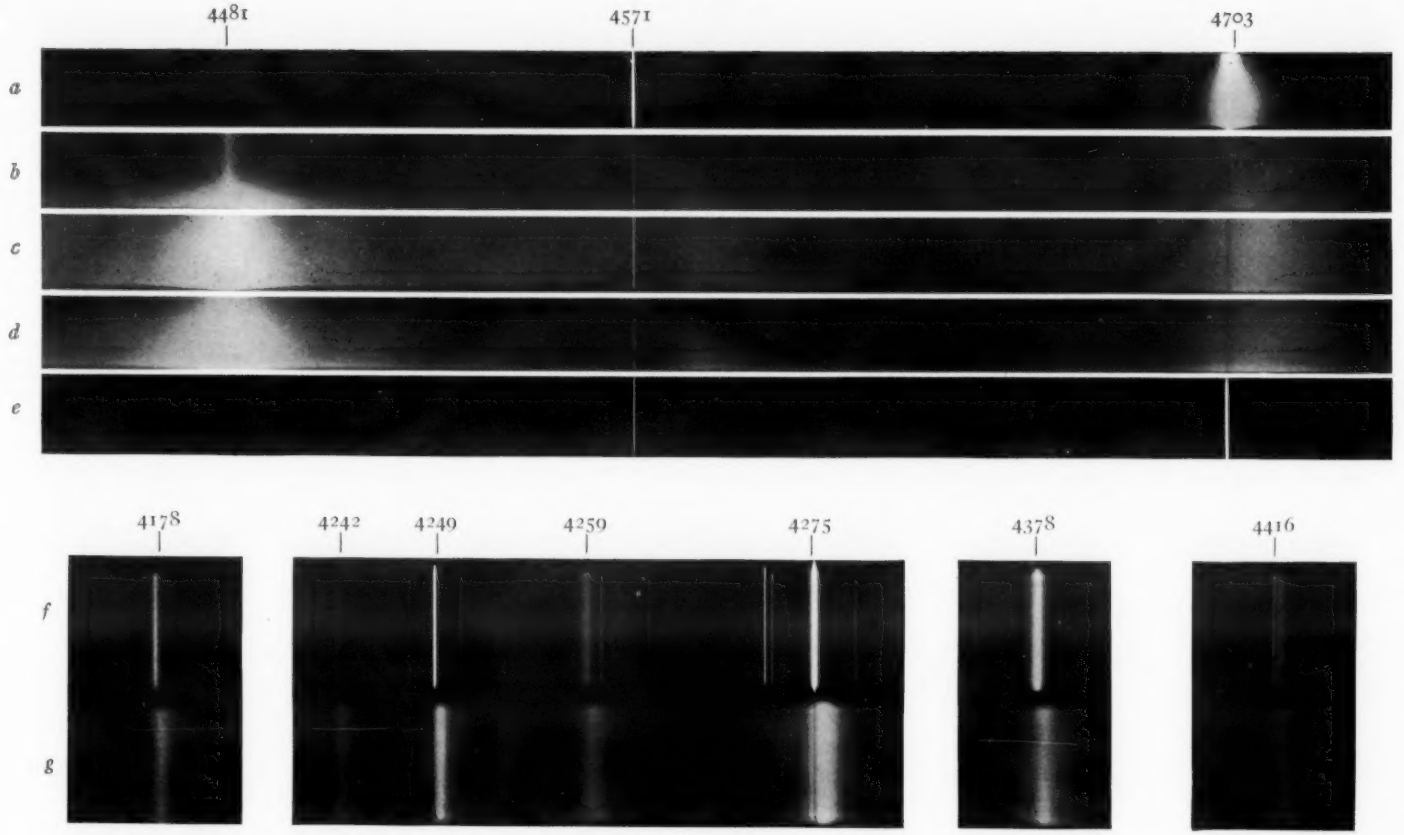
Aluminum.—The strong lines λλ 3944, 3962, spread to a great width in the high-current arc between metal rods, but when obtained as impurity lines in other spectra, they showed large red dissymmetry, with the reversal on the violet edge of the emission

[1] *Mt. Wilson Contr.*, No. 103; *Astrophysical Journal*, **41**, 373, 1915.

[2] *Astrophysical Journal*, **44**, 65, 1916.

[3] *Ibid.*, **53**, 224, 1921.

PLATE XIII



HIGH-CURRENT ARC SPECTRUM OF MAGNESIUM (*b*, *c*, *d*) AND COPPER (*g*)
LOW-CURRENT ARC SPECTRUM: *a*, *e*, AND *f*

lines. A similar dissymmetry was previously observed in the tube arc. In aluminum arcs, the gallium lines λλ 4033, 4172, are frequent impurities, and in the high-current arc appeared reversed with very strong red dissymmetry.

The strong aluminum bands from λ 4400 to λ 4900 showed an interesting absorption effect. The enhanced lines in this region are very strong in the high-current arc, and each of these appeared as a group of fine lines resembling a diffraction pattern. This was caused by the absorption of the outer envelope in which the bands are present. The enhanced line radiation appeared only in the spaces between the band lines.

Magnesium.—The appearance of the enhanced line λ 4481 and the structure of arc lines in the blue were observed. In the writer's study of the tube-arc spectrum,[1] λ 4481 was obtained with high intensity and its doublet structure was detected. The line was also very strong in the high-current arc in air, especially when the radiation near the negative pole fell on the slit. At the positive pole the line was weak, its width being that required by the two components, while near the negative pole, it sometimes spread to a width of 15 A.

This variation, together with the absence of λ 4481 from the arc between carbon terminals charged with magnesium, is shown in Plate XIII, which also illustrates the very large displacement of the high temperature line λ 4703. This line in the ordinary arc undergoes strong widening to the red when much magnesium is present, as is shown in Plate XIII*a*, but the position of the maximum is given by the point of the widened line. Plate XIII*d*, taken with small vapor density, shows the line sharp. In the high-current arc, the maximum of emission was displaced into the region to the red, ordinarily merely shaded, while the reversal remained in the position of the sharp arc line. An intensity curve for λ 4703, made with the registering microphotometer by Miss Ware, is reproduced in Figure 1. On this curve the position of the emission maximum is approximately 7 A to the red of the reversal, which appears as a notch on the slope of the curve. A displacement of similar magnitude was shown by λ 4352, but was too diffuse for measurement. The low-temperature line λ 4571 is shown also in Plate XIII. In the high-current arc, it

[1] *Mt. Wilson Contr.*, No. 73; *Astrophysical Journal*, **38**, 315, 1913.

was always narrow, but reversed unsymmetrically with the red side distinctly stronger.

Copper.—The spectrum from λ 3800 to λ 4600 was photographed with the high-current arc between copper rods 6 mm in diameter. The arc was of very brief duration, with the maximum current uncertain. The effect on some of the high-temperature lines, which tend to diffuseness in the ordinary arc, is shown in Plate IV. As a rule, these lines did not reverse, but appeared as wide, fairly symmetrical lines much displaced to the red. Some showed unsymmet-

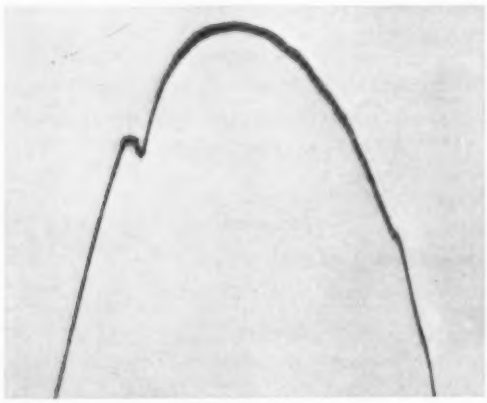


FIG. 1.—Microphotometer curve of magnesium λ 4703 in high-current arc

rical reversal, however, the best defined being λ 4275, whose reversal coincided in position with the sharp line of the ordinary arc. This showed freedom from instrumental shift and made possible a rough measurement of the displacements. These averaged 0.33 A for seven lines from λ 4100 to λ 4600. Near λ 3900 a considerable number of fainter arc lines were strongly displaced to the violet.

Sodium, D lines.—These were obtained as very weak impurity lines on several plates, and showed a reversal with the red side distinctly stronger. With the symbols used for the iron lines, they would be described as Ru_r. This is the structure most frequently found for the lowest temperature lines in the spectra thus far examined.

Oxygen and nitrogen, infra-red lines.—The oxygen triplet, λλ

7771.97, 7774.01, 7775.68, appeared in the high-current arc between iron electrodes. The lines were shaded to the red, and showed a greater increase over their strength in the ordinary iron arc than do the average iron lines.

The nitrogen lines, λλ 7423.88, 7442.56, 7468.74, in the same arc were fairly strong, with shading to the red. As a very diffuse line, λ 8216.46 also appeared. On account of the odd multiplicity found in their series regularities, these lines are assigned by Kiess[1] to the spectrum of ionized nitrogen. Their appearance in the high-current arc indicates that they belong to a lower level of the ionized atom than the powerful spark lines near λ 4600, which do not appear in this arc.

DESCRIPTION OF THE PLATES

Plate X was described on page 246. Three types of iron lines are illustrated in spectrum *b:* low-temperature lines with almost symmetrical reversals, such as λλ 5397, 5430, 5434; high-temperature lines with red displacement of the maximum, as λλ 5324, 5340, 5393; and the group *e* lines, λλ 5383, 5404, 5415, 5424, with strong violet dissymmetry and the very unusual self-reversal. Spectrum *c* is that of the high-current arc burning steadily with iron-carbon terminals, showing great intensification of the high-temperature lines and small dissymmetry.

Plate XI shows two sections of the iron spectrum in the green, the multiplet near λ 4900 and many other lines having strong red dissymmetry. Numerous lines remain narrow, while a group near λ 5100 is displaced to the violet. The degree to which the enhanced lines λλ 4924, 5018 are strengthened in the high-current arc represents the usual appearance of enhanced iron lines in the visible spectrum.

Plate XII covers a large part of the orange and red of the iron spectrum. A comparison with the ordinary iron arc, Plate XII*a*, shows many differences in relative intensity as well as numerous displacements toward red or violet. The lines which remain sharp and of nearly the same intensity in the two arcs show the usual behavior of unreversed low-temperature lines, but owing to the relatively high temperature required to produce the iron spectrum in

[1] *Science*, **60**, 249, 1924.

the red, they are seldom below Class III. The absence of the band spectrum from the high-current arc is notable throughout this region, especially near λ 6000.

Plate XIII shows in its upper section the magnesium lines, λλ 4481, 4571, 4703, these being an enhanced line and low- and high-temperature lines, respectively. Their features are described on page 261. The lower section gives some high-temperature lines of copper, with large displacements toward the red. The reversal of λ 4275 is in the position of the narrow arc line shown just above it.

MOUNT WILSON OBSERVATORY
June 1925

THE INFRA-RED SPECTRUM OF THE CALCIUM ARC *IN VACUO*

By O. SANDVIK and B. J. SPENCE

ABSTRACT

The investigation was undertaken with the following threefold object in view: (1) to study the arc *in vacuo* as a source of radiation for radiometric investigation of its spectrum; (2) to study possible differences between the spectrum of the arc *in vacuo* and at atmospheric pressure; (3) to obtain wave-lengths of new lines if they were found to exist. A very steady source of radiation for radiometric observation was developed, some differences largely in intensity between the arc *in vacuo* and at atmospheric pressure were observed, and the wave-lengths of seventeen new calcium lines beyond the wave-length 1.0 μ were obtained. More lines were present but their intensity was too small to obtain determinations of wave-length.

Notable among the contributors to the existing data on the infra-red spectra of the elements are Paschen[1] and Randall.[2] In their investigations, an open arc, a plane grating, and a bolometer or thermopile with the necessary adjuncts were employed. The spectra of many of the elements to wave-lengths between 3 μ and 5 μ were obtained by them.

In the study of the infra-red arc spectra of the elements, one is confronted at the outset with certain experimental difficulties, chief among which are the lack of steadiness of the open arc and the lack of sufficient sensitivity of the existing instruments used for detecting the weaker spectral lines.

The lack of steadiness of the source of radiation is of no particular consequence where the photographic method is employed. The effect on the photographic plate is cumulative, and a high time-rate of emission of energy, while desirable, is not a necessity. Radiometric methods, on the other hand, require a high time-rate of emission of energy and one which is constant at least during a series of observations on a spectrum line.

The following investigation of the calcium arc was undertaken with a threefold object in view: (1) to study the arc *in vacuo* as a source of radiation for radiometric investigation of its spectrum; (2)

[1] *Annalen der Physik*, **14**, 29, 625, 1909.

[2] *Astrophysical Journal*, **34**, 1, 1911.

to study possible differences between the spectrum of the arc *in vacuo* and at atmospheric pressure; (3) to obtain the wave-lengths of new lines if they were found to exist.

THE VACUUM ARC

The vacuum arc, described by Crew and McCauley,[1] seemed particularly adapted for the work, in view of the fact that visually it appeared to be remarkably steady. A preliminary radiometric survey of the spectrum revealed the fact that the arc was not as steady as it appeared, but was much steadier than the open arc. It was furthermore found that the intensity of radiation was considerably less than the arc in the open.

The chief cause of the lack of steadiness is due to lateral shifts of the arc, caused by the wandering of the hot spot on the lower or positive electrode. It was found necessary to use a 0.25-in. carbon for the lower electrode. The carbon pierced the bottom of a small zirconium silicate crucible about 1.25 in. in diameter at the top and about 1 in. deep, and passed up through the center of the crucible to about 0.25 in. above its top. The crucible was then packed with a mixture of 80 per cent calcium chloride and 20 per cent calcium oxide. Liquid calcium chloride surrounded the electrode when the arc was in operation, soon saturating the carbon and furnishing a supply of calcium. The result was an arc very rich in calcium and more intense than that obtained with the customary cored carbons impregnated with the salt of the element. The arc was operated at 15 amp. from a 220-volt supply. The pressure was maintained at 1 cm of mercury. Soon after the operation of the arc was begun, a crater of calcium oxide, 3 mm in diameter, was formed on top of the carbon, which prevented the hot spot from wandering freely. The presence of the very refractory zirconium silicate added no impurities to the spectrum. As revealed by a careful visual examination of the spectrum, potassium and sodium lines, which were expected to be found, were not present. The hot crater was too far removed from the crucible to heat it excessively.

In view of the smaller intensity of the arc *in vacuo*, it was found necessary to develop an exceedingly sensitive radiometer with vanes

[1] *Astrophysical Journal*, **39**, 29, 1914.

made of aluminum leaf to detect the weaker lines. This instrument will be described by one of the authors elsewhere.

ENSEMBLE OF APPARATUS

The radiation from the arc was brought to focus by a concave mirror on the spectrometer slit of 0.2 mm width. From the slit the radiation was incident on a concave mirror of 30-cm focal length, which rendered the radiation parallel before it fell upon the grating of 15,020 lines per inch. The surface of the grating was 50 mm × 50 mm. The radiation dispersed by the grating was sent back to the concave mirror and then brought to focus upon the 0.2-mm wide radiometer vane. The grating was mounted upon a spectrometer table designed for rapid observations.[1]

The spectrometer was calibrated by means of the sodium flame. Settings of the central image and the first four orders of the line λ 5890 A were carefully noted. These settings could be repeated with an accuracy of 0.1 division on the divided circle, corresponding to less than 0.3 A. With the slit width of 0.2 mm the radiometer vane covered a spectral range of about 5 A. For the evaluation of wave-lengths the customary expression,

$$2\lambda = 2d \cos\frac{\theta}{2} \sin\frac{\theta}{2},$$

was used. This, applied to the particular spectrometer in use, reduced to

$$n\lambda = A \sin NK,$$

where A is a constant involving the grating constant and the angle formed by the axes of the collimator and telescope, K is an instrumental constant,[2] and N the setting corresponding to a given line.

RESULTS

The investigation covered the spectral range from λ 8500 A to λ 20,000 A. This entire region was gone over as many as thirty times for the weaker lines. The wave-lengths of thirty lines were measured, seventeen of which were new lines. The results are incorpo-

[1] *Journal of the Optical Society of America*, **8**, 1923. [2] *Loc. cit.*

rated in Table I. The first column gives the spectrometer settings. The second column shows the relative intensities of the various lines in the vacuum arc in terms of deflections in millimeters of the radio-

TABLE I

1	2	3	4	5	6
Spectrometer Setting	Intensities	Sandvik λ in A.U.	Randall	Paschen	Meggers
			Air Arc λ in A.U.	Air Arc λ in A.U.	λ in A.U.
2917.0*	100	8497.3±1.0	.....	8499.0	8497.98
2933.0	400	8542.9±1.0	.....	8542.6	8542.06
2974.8*	450	8661.8±1.0	.....	8662.6	8662.10
.....	.....	.....	.....	9250.8	.....
.....	.....	.....	.....	9546.8	.....
.....	.....	.....	.....	9694.5	.....
3570.0†	200	10344.1±0.5	10345.0	10345.0	.....
3951.0	150	11406.9±1.0	.....	.....	.....
5014.0‡	(?)	14302.1(?)	14278.0	.....	.....
.....	.....	.....	16144.8	16144.8	.....
.....	.....	.....	16162.2	16162.2	.....
.....	.....	.....	16200.0	16200.0	.....
.....	.....	.....	.....	16432.6	.....
5952.0*	22	16756.7±0.4	.....	.....	.....
6761.0§	45	18785.9±0.3	.....	.....	.....
6784.0	35	18841.7±1.0	.....	.....	.....
6804.0	8	18897.4	.....	.....	.....
6814.0	13	18915.1±0.4	.....	.....	.....
6841.0*	10	18981.1±1.0	.....	.....	.....
6850.0§	16	19007.4±1.0	.....	.....	.....
6872.0*	10	19056.8±1.5	.....	.....	.....
6890.0*	23	19100.7±1.0	.....	.....	.....
6897.0§	8	19116.4±1.5	.....	.....	.....
6976.6	35	19311.0±1.0	19310.3	19310.6	.....
7035.1	75	19452.5±1.0	19452.6	19452.6	.....
7056.0§	30	19502.5±1.5	.....	.....	.....
7058.0	8	19507.5±1.1	19506.8	19507.1	.....
7169.5	80	19775.2±1.6	19771.1	19777.4	.....
7204.0‡	40	19857.3±2.0	19856.1	.....	.....
7207.0*	30	19864.4±0.8	19864.1	19859.9‖	.....
7228.0*	50	19915.0±2.0	19917.3	.....	.....
7237.0*	12	19936.1±1.6	19935.2	19935.8	
.....	.....	.....	.....	19946.8	.....
7251.0§	9	19970.9±1.5	.....	.....	.....
7331.0*	8	20159.7±1.5	.....	.....	.....
7496.0*	10	20547.0±2.4	.....	.....	.....
7526.0§	8	20617.0±2.5	.....	.....	.....
7550.0§	11	20673.0±2.5	.....	.....	.....

* More intense in vacuum arc; voltage supply, 220 volts.

† More intense in open arc; current, 15 amp.

‡ Observed in open arc only; pressure, 1 cm *Hg*.

§ Observed in vacuum arc only.

‖ Probably two lines whose wave-lengths are λ 19856.9 and λ 19864.6 A.

meter vane. The third column contains a list of the lines observed with an estimate of the degree of accuracy in making observations. These estimates are based on the deviations from the most probable value. Some preliminary observations for the open arc, communicated to A. Fowler[1] by H. M. Randall, are listed in the fourth column. The fifth column presents the lines observed by Paschen[2] in this region, also with the open arc. The last column contains three lines due to ionized calcium measured photographically by Meggers,[3] a group of lines at λ 9250.8, λ 9546.8, and λ 9694.5 A, and another group of four lines, λ 16144.6, λ 16162.2, λ 16200.0, and λ 16432.6 A, reported by Paschen were not observed in this investigation. It is probable that these lines are more intense in the open arc. Indications were obtained of the first group of three lines but these were too faint to allow reliable measurements.

Several lines, not included in the foregoing list, were observed in the region from 1.70 μ to 2.20 μ. These lines were too faint to allow reliable measurements. No line whose intensity was less than 8 mm scale-divisions is included in the table. The value of λ 14302.1 A is doubtful. This line was observed only in the open arc.

In comparing the relative intensities of the lines, it is interesting to note that of the three lines due to ionized calcium, the lines λ 8497.3 and λ 8661.8 A, although very intense in the vacuum source, were faint in the open arc, while the line λ 8547.9 A had practically the same intensity in both sources. The lines λ 18781.5 and λ 19007.4 A were too faint to be observed in the open arc. Other lines having higher intensities in the vacuum arc are included in the table.

EASTMAN KODAK COMPANY AND
NORTHWESTERN UNIVERSITY
April 1925

[1] *Series in Line Spectra*, chap. xiv, p. 121. [2] *Loc. cit.*
[3] *Bulletin of the Bureau of Standards* (Washington, D.C.), No. 312, 1923.

THE LAW OF SUN-SPOT POLARITY[1]

By GEORGE E. HALE and SETH B. NICHOLSON

ABSTRACT

Magnetic observations of sun-spots.—The magnetic polarities of about 2200 sun-spot groups, observed on Mount Wilson between 1908 and 1925, are discussed in this paper. The polarities and approximate field-strengths are determined by daily observations of the Zeeman triplet λ 6173 in the second-order spectrum of the 75-foot spectrograph of the 150-foot tower telescope. *Invisible spots* and the method of observing them are also described. A *revised scheme of magnetic classification* of sun-spots, grouped as unipolar, bipolar, and complex, is described, and many individual cases are discussed and illustrated. Tables III, IV, and V give the magnetic classification of 2174 spot groups, the percentage and frequency of the groups of each class, and the magnetic classification of the groups at formation.

Law of sun-spot polarity.—Discussion of the polarities of spots belonging to the last three 11½-year cycles leads to the following law, which represents all of the observations with only 41 exceptions out of 1735 groups:

The sun-spots of a new 11½-year cycle, which appear in high latitudes after a minimum of solar activity, are of opposite magnetic polarity in the northern and southern hemispheres. As the cycle progresses the mean latitude of the spots in each hemisphere steadily decreases, but their polarity remains unchanged. The high-latitude spots of the next 11½-year cycle, which begin to develop more than a year before the last low-latitude spots of the preceding cycle have ceased to appear, are of opposite magnetic polarity.

Thus while the well-known 11½-year interval correctly represents the periodic variation in the number or total area of sun-spots, the full sun-spot period, corresponding to the interval between the successive appearances in high latitudes of spots of the same magnetic polarity, is 23 years. This may be called the "magnetic sun-spot period," to distinguish it from the 11½-year frequency period.

In a previous paper[2] we have described our methods of determining the magnetic polarity and field-strength of sun-spots and the magnetic classification of 970 spot groups observed during the years 1915–1917. We have also called attention to the remarkable reversal of magnetic polarity observed at the advent of the spots of a new 11½-year cycle in 1912, and indicated that at the conclusion of this cycle the law of sun-spot polarity should become apparent. As our observations from 1917 to 1924 have fully confirmed the earlier ones, showing at a second sun-spot minimum a general reversal of polarity corresponding to that which occurred in 1912, we are now in a position to formulate a polarity law, the validity

[1] *Contributions from the Mount Wilson Observatory*, No. 300.

[2] Hale, Ellerman, Nicholson, and Joy, "The Magnetic Polarity of Sun-Spots," *Mt. Wilson Contr.*, No. 165; *Astrophysical Journal*, **49**, 153–178, 1919.

of which can be tested in future cycles of solar activity. Brief summaries of our conclusions have already been published,[1] but without the detailed results given in the present paper. This also includes a revised outline of our scheme of classification and a discussion of various special cases which emphasizes the necessity of using a rational method of grouping sun-spots with respect to their magnetic polarities and the distribution of the accompanying flocculi.

METHOD OF OBSERVATION

The method of observation which has been used to determine the magnetic polarities and field-strengths of about 2200 spot groups during the period 1908–1925 is fully described in the article mentioned and may be briefly recapitulated here. The 150-foot tower telescope on Mount Wilson forms an image of the sun about 16.5 inches (43 cm) in diameter on the slit of a spectrograph of 75 feet (22.9 m) focal length, mounted vertically in a well beneath the tower. The iron line λ 6173.553 is observed daily in the spectra of all spots, large and small, comprised in the various groups present on the sun. In a magnetic field this line is a triplet, and the polarity of the spot in question is determined by noting visually which of the *n*-components, *R* (to the red) or *V* (to the violet), is transmitted by a given strip of a compound quarter-wave plate, used in connection with a Nicol prism above the slit of the spectrograph. The distance between the *R*- and *V*-components, measured with a micrometer, gives the approximate field-stength at the corresponding point in the spot. This is expressed in units of 100 gausses. Thus V_{17} means that the violet component is transmitted, and hence that the polarity of the spot is "south" (south-seeking pole) or negative, while the field-strength is approximately 1700 gausses.[2]

These observations are entered on a pencil sketch of the solar image and its spots, made by tracing their outline on a large sheet of paper supported above the slit at the focus of the tower telescope.

[1] For these preliminary accounts see *Nature*, **113**, 105–112, 1924, and *Proceedings of the National Academy of Sciences*, **10**, 53–55, 1924.

[2] We now give polarities as "north" and "south" instead of "positive" and "negative," because several writers have supposed the latter terms to refer to positive and negative charges in the corresponding spots, in spite of the fact that our papers have given no evidence to support such an assumption.

Drawings on wax from these are being made for reproduction on a smaller scale in a volume which will give our complete magnetic record of sun-spots for the period 1917–1925. One of these drawings is shown in Figure 1. In order that the polarity in various parts of the larger spots may be distinguished at a glance, the regions that have "south" polarity are covered with small crosses, while those of "north" polarity are dotted.[1]

In the detection of the very weak fields that betray the existence of invisible spots (see p. 280), an auxiliary half-wave plate, oscillated back and forth across the slit by means of a small electric motor, is used to cause the slight widening of the line to appear alternately toward red and violet, thus rendering the effect more readily visible.

Certain precautions necessary in the determination of polarities are mentioned in the paper cited, and need not be repeated here. In general, the angle between the lines of force and the sun's surface decreases from about 90° near the center of the umbra to about 0° near the edge of the penumbra. For this reason, polarity observations near the limb are difficult for large spots and impossible for small ones.

In the designation of spot groups it has not been possible to use the Greenwich serial numbers, partly because of the interruption in their publication during the war, and also because our magnetic scheme must frequently combine in a single group spots that would otherwise be classed separately, or vice versa. Our spot positions, however, are only roughly approximate, and serve merely for purposes of identification. The Greenwich measures should be substituted for them in all work involving accurate heliographic positions.

THE MAGNETIC CLASSIFICATION OF SUN-SPOTS

In our magnetic system, spot groups are divided into three classes, distinguished here as "unipolar," "bipolar," and "complex" (formerly called "multipolar").

Unipolar groups are single spots or groups of spots of the same magnetic polarity. The three subdivisions of this class are deter-

[1] Through an unfortunate error, which for some unaccountable reason was not detected until about 300 of the engravings had been completed for the printer, the crosses (which resemble plus signs) were shown in the regions of south or negative polarity, instead of in those of north or positive polarity, as originally intended.

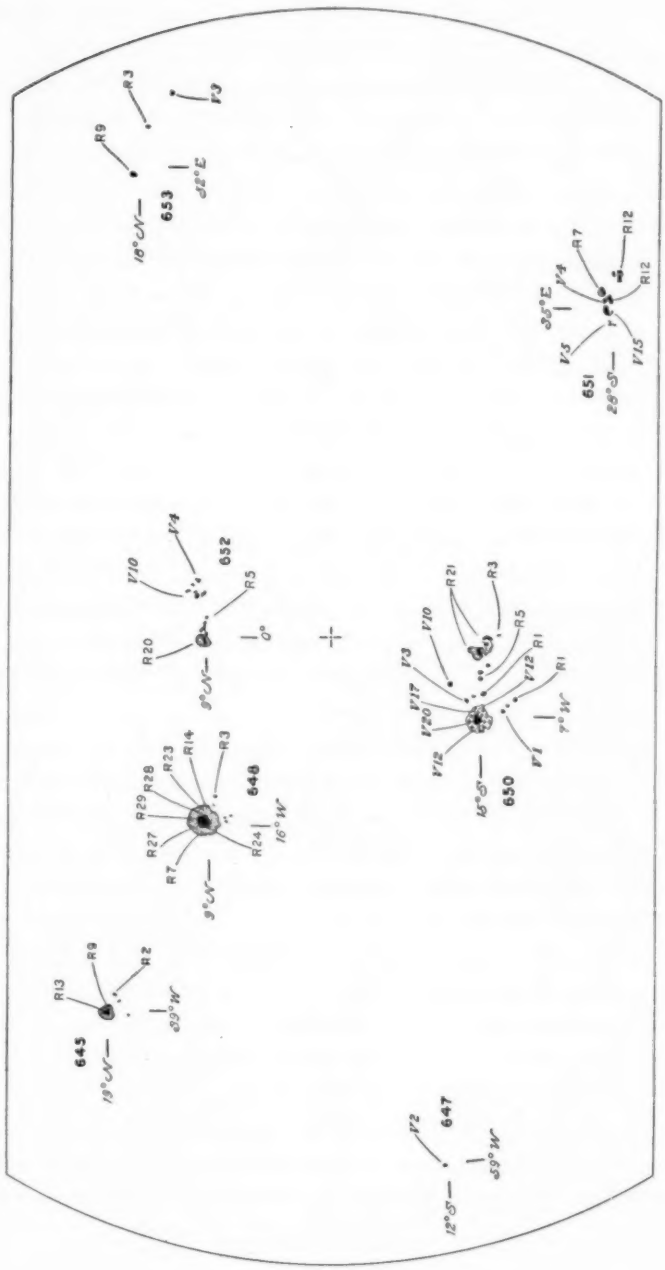


FIG. 1.—Record of sun-spot polarities, May 14, 1917

mined by the position of the group with respect to the surrounding calcium flocculi: (a) those for which the distribution of the flocculi preceding and following the group is fairly symmetrical; (ap) those which are followed by a distinctly elongated mass of flocculi; (af) those which are preceded by a distinctly elongated mass of flocculi.

Bipolar groups consist, in their simplest form, of two spots of opposite polarity, the line joining them generally making a small angle with the solar equator. Usually, however, the bipolar group consists of a stream of spots, of opposite polarity in the preceding and following parts. The change in polarity is generally near the center of the stream, but it may be on either side of the center. Bipolar groups are subdivided as follows in accordance with the area and distribution of their constituent magnetic fields: (β) those in which the preceding and following members, whether single or multiple, are approximately equal in area; (βp) those in which the preceding member is the principal component of the group; (βf) those in which the following member is the principal component of the group; and ($\beta\gamma$) those in which the bipolar characteristics are shown, but with no clearly marked dividing-line between the groups of opposite polarity. This includes cases where the preceding or following members are accompanied by small spots of opposite polarity.

Rigorously defined, the principal component of a bipolar group, whether single or multiple, is that for which the total integrated field-strength is the greater. In daily practice it would be almost impossible to make a sufficient number of measures of field-strength and area to determine this quantity accurately. Up to a certain area, the field-strength is almost directly proportional to the diameter of the spot, with its maximum intensity near the middle of the umbra, decreasing to zero just beyond the outer edge of the penumbra. But when the spot is split into several members, the maximum field-strength in any one of them is less than that shown by an unbroken spot. Accordingly, in a bipolar group consisting of a large single spot followed by several smaller spots having the same total area, the preceding spot would be regarded as the principal component. The integrated field-strength as thus estimated, not actually measured, is sufficient for classification.

Groups ap and af are frequently accompanied by invisible spots,

or local magnetic fields, in the place of the absent component. These do not appear in the tabulated classification, however, because of the difficulty of detecting invisible spots, especially when the definition of the sun's image is poor.

Complex groups are those in which the polarities are so irregularly distributed that they cannot be classified as bipolar. Their number is small but includes some of the largest and most active spot groups. As already noted under bipolar groups, the presence of occasional small companions, which play a minor part in these or in unipolar groups, is disregarded in their classification.

In distinguishing these various classes and their subdivisions, it is thus evident that the daily observations of the Zeeman effect in spot spectra must be supplemented by photographs of the calcium flocculi. Even with both of these guides it is sometimes difficult to assign the numerous spots in crowded regions of the sun to their respective groups. To make this clear and to illustrate the danger of grouping spots without these aids, we give a number of illustrations of various deceptive cases drawn at random from our records. Because of the peculiar significance of bipolar groups, of which all spots may be regarded as variants, it will be advantageous to discuss them first.

BIPOLAR GROUPS

The fundamental importance of bipolar groups, on which our scheme of classification rests, has been greatly emphasized by the continued accumulation of observational data, the discovery of invisible spots, and the life-history of spots of various types. As we have stated, bipolar groups often consist of long streams of spots, comprising many members, and betraying no evidence in the direct telescopic image of subdivision into two distinct groups of opposite polarity. The application of the spectroscopic test instantly discloses the magnetic distinction between the constituent spots and the overwhelming tendency of those of like polarity to cluster together at opposite ends of the stream. It is quite unsafe, however, to apply the term "bipolar group" to paired spots or to binary groups of small spots, as some solar observers have done without testing the polarities. An examination of certain typical groups will make this point clear.

A simple bipolar group, with widely separate components, is No. 2091, August 18, 1924, illustrated in Figure 2. Here we see two nearly equal spots at 15° and 18° N. latitude, opposite in polarity, and with field-strengths *V* 2400 and *R* 2000 gausses, respectively. No distinct companions are present, but on August 17, and again on August 20, a small spot was observed between the principal members. It was easy to recognize these widely separated spots as the members of a single bipolar group, not merely because of their opposite polarity but also because of the distribution of the flocculi between them.

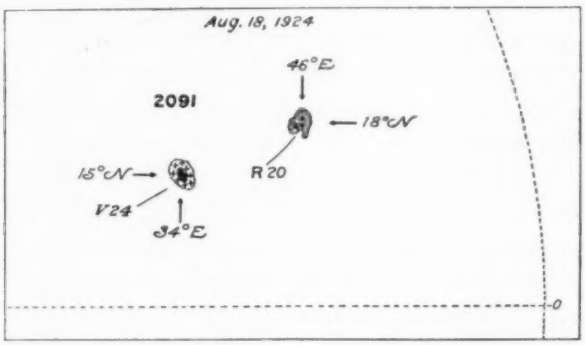


FIG. 2.—Simple bipolar group with widely separated components. No. 2091, August 18, 1924.

These spots are much more widely separated than the components of most simple bipolars, but even longer groups sometimes occur, the members of which, without spectroscopic tests, might be classified as separate spots. In most bipolar groups or streams many small spots are present, and the consistency with which the components of the eastern and western parts of the streams agree in polarity is very striking. A good example may be taken from the polarity record of June 19, 1917, which also affords several other typical instances of spot classification.

The bipolar group 687 stood centrally in the midst of a large aggregation of spots, easily separated into three magnetic groups (Fig. 3, No. 5). Its leading member appeared at the east limb on June 14 at 12° N. latitude, when its preceding edge was recorded as R_3 and its umbra as $(R+V)_{15}$. This appearance in the same spot

of both *n*-components, as explained in our previous article, was due to the fact that the observation was made with Nicol and quarter-wave plate on the umbra near the limb, where the line of sight was nearly at right angles to the lines of force. On the following day the whole group was visible, the leading component recorded as R_{17} and

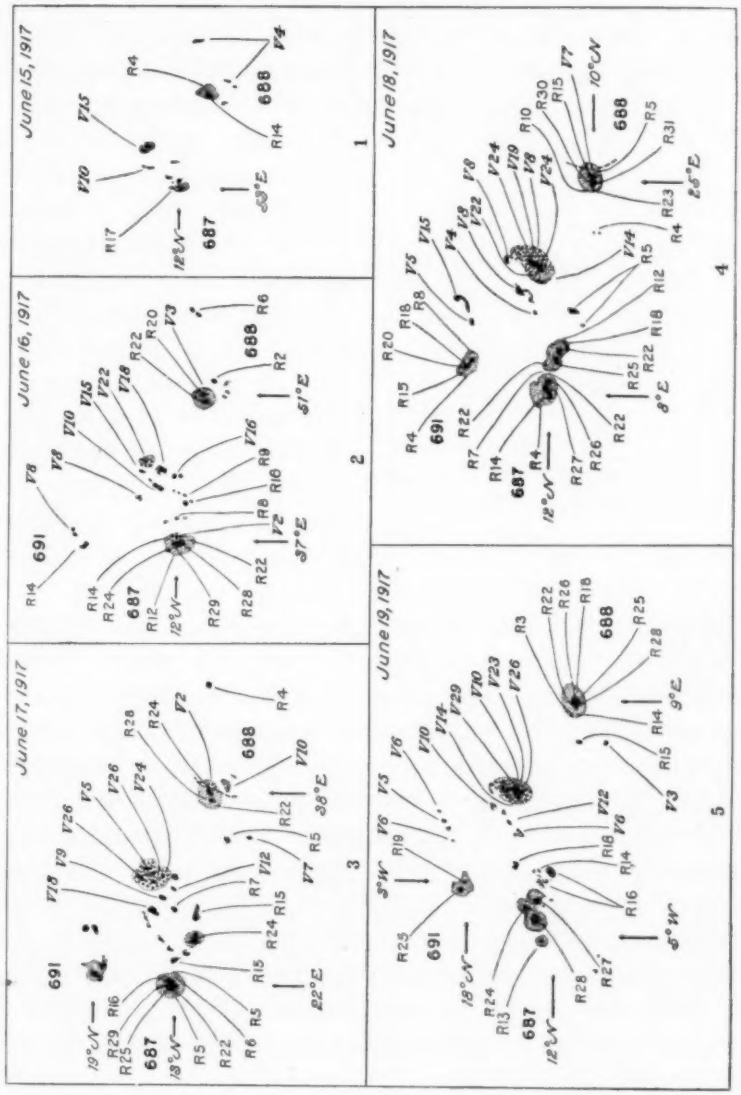


FIG. 3.—Magnetic polarities of the spot groups Nos. 687, 688, and 691, June 15–19, 1917

the two following components as V_{10} and V_{15}, respectively (Fig. 3, No. 1). A few minor companions were also present. Following this bipolar group about 2° S. and 14° E. was another group (No. 688) with a preceding member R_{14}, followed by some small V-companions. On June 16 group 687 contained many spots, all of the western ones recorded as R, and all of the eastern ones as V, the dividing-line being near the center of the stream. Another small bipolar group (No. 691) had appeared at 18° N. latitude, its preceding member R_{14} and its following member V_8. On June 17, as Figure 3, No. 3, shows, both 691 and 687 had many constituents, but the consistent distribution of their polarities leaves no doubt regarding their correct classification as bipolar groups. No. 688 is obviously a separate group, but its classification is less certain, as it was preceded and followed at various times in its career by small companions, both R and V. The subsequent appearance of these groups is shown in Figure 3, Nos. 4 and 5.

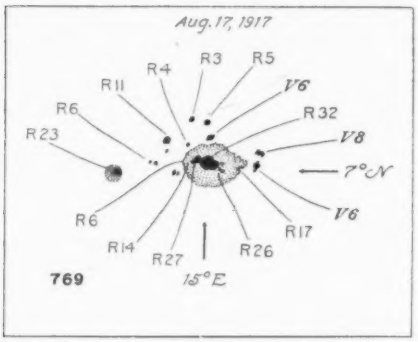


FIG. 4.—Magnetic polarities of the spots in group No. 769, August 17, 1917.

Before leaving bipolar spots, it is desirable to call attention to odd configurations, almost sure to be wrongly classified unless the polarities are known. No. 769, for example, might be called for a time a bipolar group, but not such as it appears. During several days on and after August 17, 1917 (Fig. 4), it might easily be mistaken for a βf-spot, though in fact the two principal members were on that date R_{23} and R_{32}, respectively. Several small spots at the following end of the group, which persisted until August 19, were opposite in polarity to the two large spots, and lead us to classify the whole group as βp from August 15 to 17. But after August 17 the rapid separation of the principal components and the appearance of other small V-spots, the largest (August 18) just preceding the largest umbra, seem to call for classification as two groups or as one group of mixed polarity

As extreme cases of unusual grouping, we may mention such pseudo-bipolars as No. 796, which on September 4, 1917 (Fig. 5), would surely have been regarded as a true bipolar if classified without spectroscopic tests. The large leading spot at 16° S. latitude was recorded as V_{29}, thus corresponding to the bipolar rule for regular spots at that time. The large following spot, however, instead of being R, was actually V_{24}. Just preceding it was a very small spot R_3, presumably the following companion of V_{29}, making with it a βp-group. Behind it were several small spots, one of which was V_4, followed by two others, recorded as R_5 and R_8. This, therefore, seems to be another βp-group. On September 6 all of the small companions had disappeared, and the eastern spot was reduced to V_9. The next day it had disappeared. Another deceptive case is group No. 1744, as it appeared on September 29 and 30, 1920. The two principal spots, V_{25} and V_{26}, 12° S. (Fig. 6, No. 2), were formed by the rapid separation of the preceding and following parts of a single large spot, which on September 25 (Fig. 6, No. 1) with its many small companions of both polarities, formed a complex group.

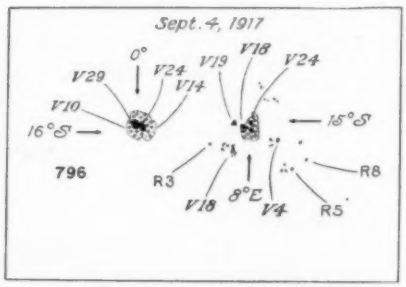


FIG. 5.—Pseudo-bipolar group No. 796, September 4, 1917.

Invisible spots.—In a large majority of bipolar groups the preceding spot is larger than the following one, which often disappears completely, leaving only the preceding spot followed by a train of flocculi. Sometimes the following spot has an intermittent existence, repeatedly appearing and disappearing. This peculiarity led us to search for local magnetic fields in the flocculi behind spots, on the hypothesis that an appreciable field might conceivably be produced by a vortex in which the cooling due to expansion is not sufficient to cause a visible darkening of the photosphere.

Such a field would be betrayed by a slight widening of λ 6173, rendered unsymmetrical by cutting off the red or violet n-component with a Nicol and quarter-wave plate. As the effect may still be so

slight as to escape detection, an auxiliary half-wave plate, oscillating or rotating above the quarter-wave plate, is used to cut off in quick succession the red and violet components, thus setting the line into vibration at the point in question. This simple device has served admirably to reveal invisible spots in bipolar groups, before and after the visible stage, and in some cases where visibility was never attained.

The bearing of these local fields on the nature of sun-spots will be discussed in a subsequent paper. From the standpoint of classifi-

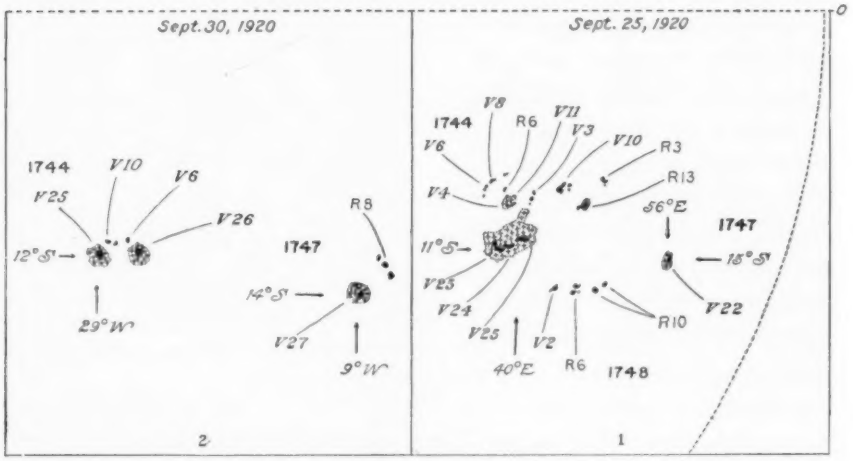


FIG. 6.—Pseudo-bipolar group No. 1744, September 25 and 30, 1920

cation, with which we are now exclusively concerned, they are seen to strengthen the evidence that some 90 per cent of all sun-spots are either bipolar or tend toward this form. Hardly 10 per cent of all spots are strictly unipolar, consisting of single spots or groups of the same polarity symmetrically surrounded by flocculi. Between these and the true bipolar groups we find single spots or unipolar groups followed (*ap*) or preceded (*af*) by flocculi, and in these flocculi invisible spots sometimes occur. If a persistent search for visible spots were made with the best of seeing and a larger solar image and higher dispersion than we employ, it is probable that great numbers of them would be found, especially in the flocculi following large unipolar spots.

UNIPOLAR SPOTS

Our previous paper, together with the foregoing remarks on invisible spots, perhaps describe sufficiently the characteristics of unipolar groups from the standpoint of classification. Some illustrations of scattered unipolar streams or groups may be added, however, to supplement what has already been said regarding pseudo-bipolars.

Group No. 2071, when first observed for polarity near the east limb on June 28, 1924, at 33° N. latitude, consisted of two spots, V_{15} and V_{14}. On June 30 the following spot had split in two, and the next day three small companions appeared, of undetermined polarity. On July 3 the group contained seven members, all *V* but two small spots, R_4 and R_2, between and slightly to the north of the two largest spots, then V_{24} and V_{20}. On July 6 Nicholson found all the widely scattered components to be of the same polarity, the small *R*-spots having disappeared (Fig. 7).

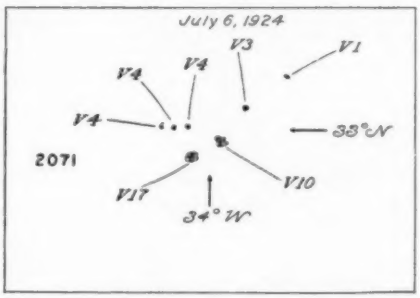


FIG. 7.—Scattered unipolar group No. 2071, July 6, 1924.

No. 697 (17° N.) is an interesting case (Fig. 8). First seen at the east limb on June 23, 1917, it had advanced far enough upon the disk on June 25 to permit of reliable polarity tests. These showed each of the three umbrae in the S-shaped preceding member to be R_{28}, and these were followed by two small spots, R_3 and R_6, followed again by three spots, V_{15}, V_6, V_8 (Fig. 8, No. 1). The next day (Fig. 8, No. 2) the preceding spot was splitting into three members, R_{26}, R_{26}, R_{22}, which on June 28 (Fig. 8, No. 3) were widely separated and followed by a faint spot without umbra V_{10}, and a small spot R_{17}. On June 30 (Fig. 8, No. 4) all the scattered members were decreasing in size, and all were *R*. This process of disintegration continued on July 2 (Fig. 8, No. 5), and on July 3 (Fig. 8, No. 6) the group was reduced to two small members, resembling a bipolar, but both were recorded as R_6. The small *R*-spot following to the south, at 10° N. latitude, was classified as a separate group.

No. 802, 18° N. (Fig. 9, No. 1), which was the return of a large γ-group observed in August, 1917, with curiously mixed polarities, also behaved in an exceptional manner in September. On September 3 (Fig. 9, No. 1) it appeared like a fairly long bipolar group, but with the exception of certain small *R*-spots south and

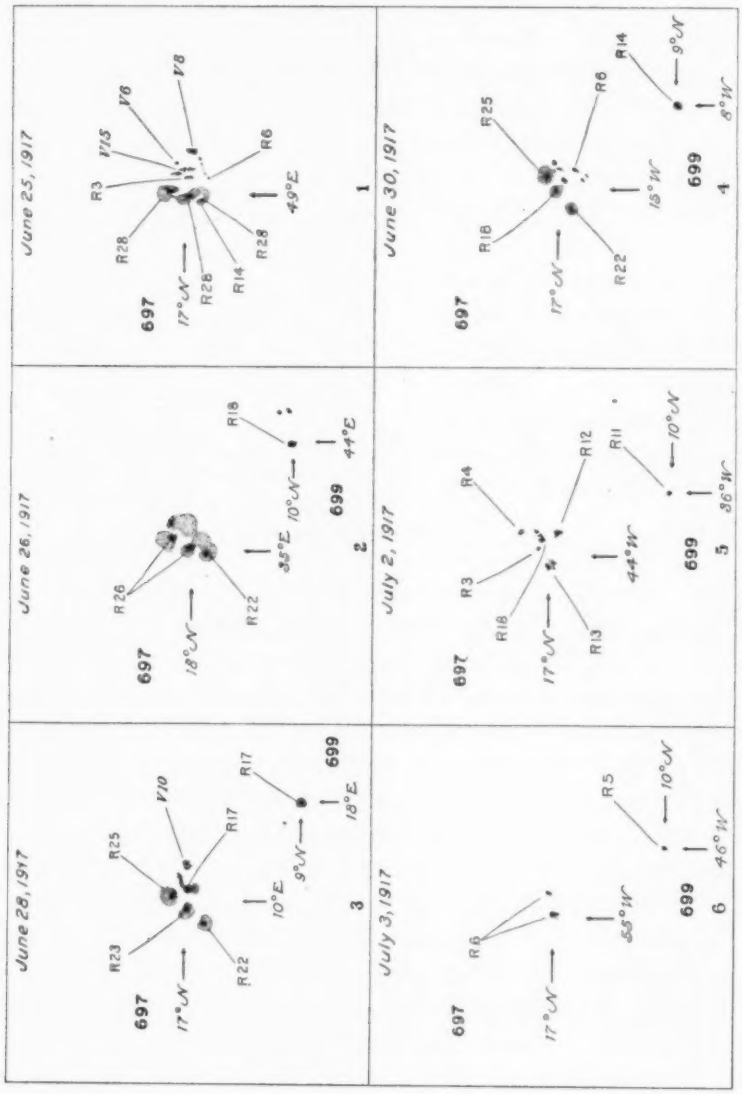


FIG. 8.—Development of groups Nos. 697 and 699, June 25—July 3, 1917

preceding, which we regard as another group (805), all its members were *V*. On September 4 (Fig. 9, No. 2) No. 802 was an odd combination, the preceding member showing V_{17} on one side and R_{18} on the other, with all the other members *V* except two in their midst, R_3 and R_6. The next day (Fig. 9, No. 3), however, the group had become an orderly bipolar, with *R* preceding and *V* following members. On September 6 the *R*-members had disappeared, and all of the spots were *V*. A day later only two of these, V_{14} and V_6, were left. One of these had disappeared on September 8, and on September 9 the last spot of the group was gone.

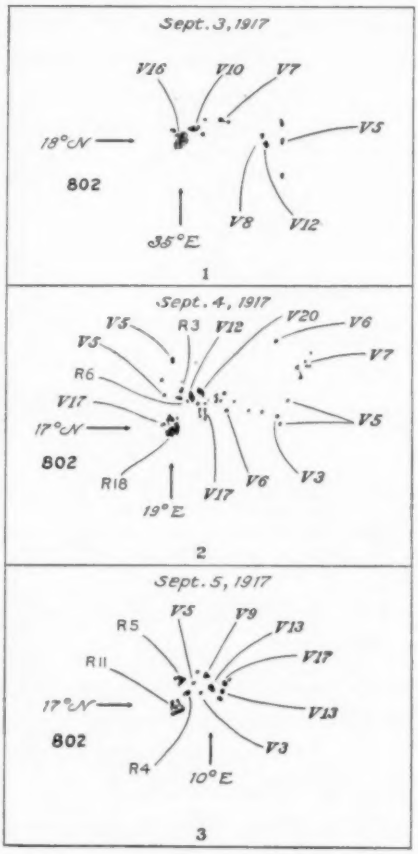


FIG. 9.—Complex group No. 802, September 3–5, 1917.

COMPLEX GROUPS

In a subsequent article on the nature of sun-spots various important characteristics of $\beta\gamma$- and γ-groups will be discussed, including their frequency in different parts of the sun-spot cycle, their area and heliographic distribution, the inclination of their axes to the solar equator, the influence of rapid development and possibly of neighboring spots, and the customary presence in them of eruptive phenomena. Here we are concerned solely with questions of classification bearing on the determination of the polarity law, and complex groups will accordingly be considered from this standpoint.

Of the 2025 spot groups observed magnetically from 1915 to

date, and included in this discussion, 3.0 per cent have been classed as $\beta\gamma$-groups and 0.8 per cent as γ-groups. They are thus too few in number to hamper the certain determination of the polarity law, but it is important to observe how they may develop out of α- and β-groups.

The chief characteristic of most complex groups is the heterogeneous distribution within them of spots of opposite polarity. They thus stand in striking contrast with α-(unipolar) groups, comprising a single spot or cluster of spots of the same polarity, and β-(bipolar) groups, consisting of two such clusters, preceding and following, of spots of opposite polarity. We find occasional $\beta\gamma$-groups, with definite bipolar characteristics but including some small spots of opposite polarity associated with the preceding or following members. In general, the components of all these groups, whether large or small, are of the same polarity in all parts of each spot, but in some γ-groups spots are present which show sharply bounded regions of opposite polarity within the same penumbra.

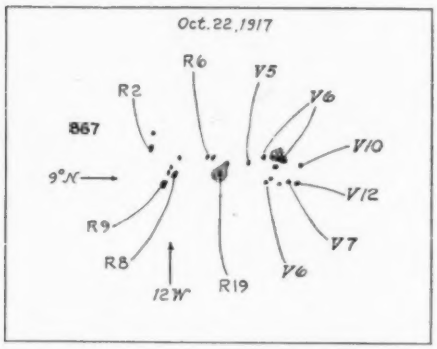


FIG. 10.—Bipolar group No. 867, October 22, 1917.

In visual or photographic observations of long trains of spots, especially those which exhibit no clustering tendency at the opposite ends of the train, we find no clue to the correct classification unless we apply the magnetic test. Take, for example, No 867 (9° N.), as observed on October 22, 1917 (Fig. 10). The polarities show this to be a bipolar group, though it so little resembles a simple bipolar such as No. 2091, observed on August 18, 1924 (Fig. 2). Sometimes the preceding and following members of bipolar groups may actually overlap, without transformation of the group into the γ-class. No. 622, as observed by Joy on April 12, 1917, is a good illustration of this (Fig. 11, No. 1). On the previous day the spots of opposite polarity were well separated into preceding and

following members, and later the bipolar nature of the group appeared even more clearly (Fig. 11, No. 2). But sometimes we observe the rapid development of a bipolar group into one of mixed polarity.

Thus No. 848 (21° N.), which suddenly broke out on the disk on October 5, 1917, was found by Ellerman to be bipolar (Fig.

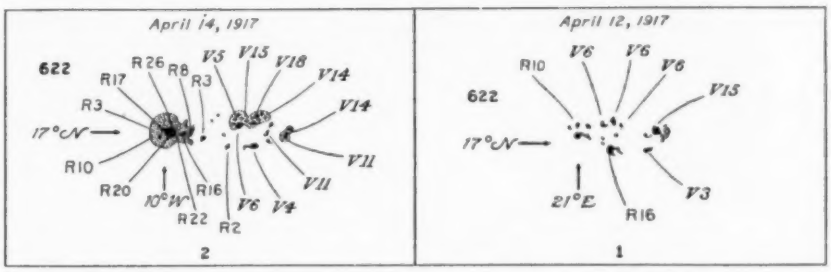


FIG. 11.—Bipolar group No. 622, April 12 and 14, 1917

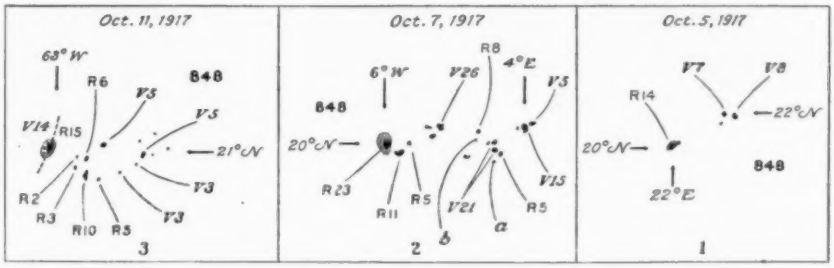


FIG. 12.—Transformation of a bipolar into a complex group, No. 848, October 5–11, 1917.

12, No. 1). The next day, when additional following members had appeared, a small spot R_3 was detected to the east of another small spot, V_6. On October 7 the group had greatly increased in size, and its complex character was apparent (Fig. 12, No. 2). Great activity prevailed between the small *V*- and *R*-spots near the following end of the group (*a*, Fig. 12, No. 2), marked by a brilliant eruption showing a violet displacement of *Hα*, corresponding to an upward velocity of 250 km per second, and a fine "bomb" not far away (*b*, Fig. 12, No. 2). On the next two days the group was even more

complex, and frequent bombs were seen near its center. On October 10 the polarities were still mixed, but on the following day, when nearing the west limb, the group had returned to the bipolar type (Fig. 12, No. 3).

Another case representing a change of type may also be described. No. 631 (Fig. 13), when first observed magnetically by Joy on April 19, 1917, appeared as a bipolar, with a large preceding spot, R_{18} accompanied on the north by two small spots R_5 and

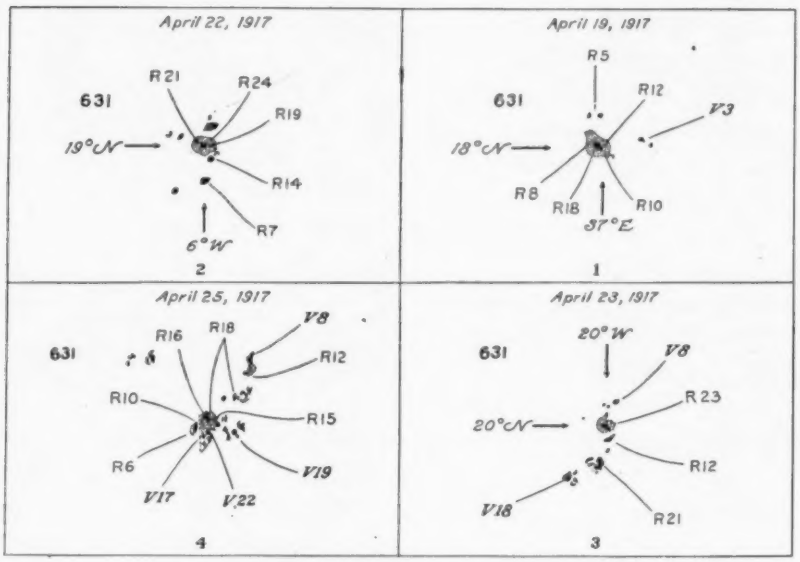


FIG. 13.—Changes in type of group No. 631, April 19–25, 1917

followed by two small spots V_3. This bipolar condition persisted until April 22 (Fig. 13, No. 2), when the two following spots had disappeared and the several preceding members, the largest of which was R_{24}, were all R, scattered over a considerable area. On April 23 (Fig. 13, No. 3) the R-members were preceded by a spot recorded by Ellerman as V_{18}, while another spot, V_8, appeared north of the largest member of the group, then R_{23}. On this date the group would naturally be classified as of mixed polarity. The next day the two umbrae of the enlarged preceding spot were found by Ellerman to be V_{13} and V_{12}, respectively, while the spot to the north was

V_9, the group thus remaining of the γ-type, with the four other members R_{22}, R_{23}, R_5, and R_4, respectively. On April 25 (Fig. 13, No. 4),

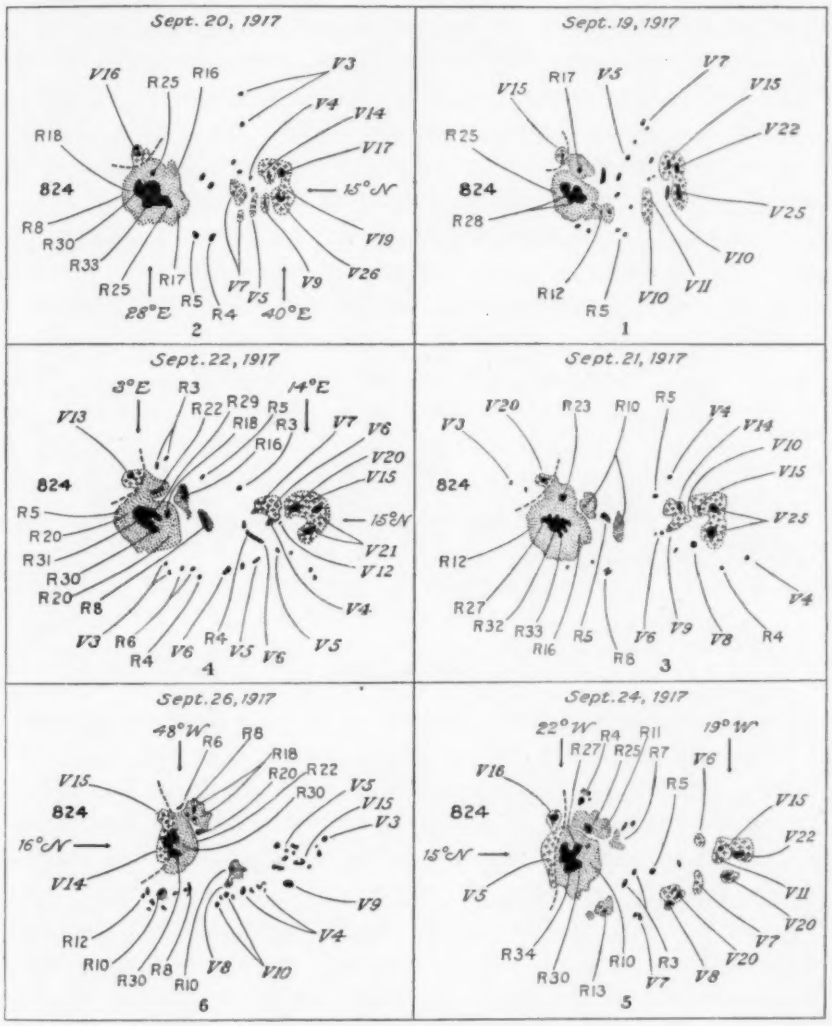


FIG. 14.—Complex group No. 824, September 19–26, 1917

the last day of observation, the polarities were similar, but the largest spot, R_{18}, had overtaken and united with the preceding spot, now V_{22}, while a similar junction had occurred to the north between

R_{12} and V_8. Thus this group, on the strength of a single day's observations, would be classified as a regular bipolar (βp) on April 19, 20, and 21; as a unipolar (αf) on April 22; and as a complex group of mixed polarity on April 22, 23, 24, and 25.

We have thus advanced by easy stages from α- and β-groups to those curious spots of the γ-type in which both polarities are sometimes found within the same penumbra. Two remarkable illustrations of this kind were given in our previous paper,[1] and many others might be added; it will suffice to mention briefly three cases.

No. 824 (16° N.) appeared at the eastern limb on September 16, 1917. If, as its position suggested, it was a return of 781, its previous history is unimportant, as this was a small group usually

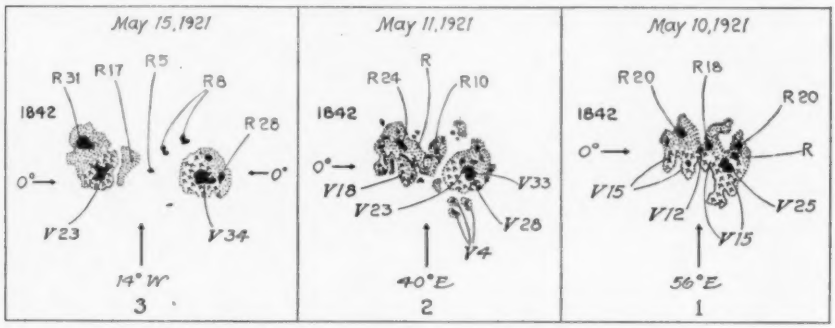


FIG. 15.—Complex group No. 1842, May 10–15, 1921

classed as α, once as β, and once as γ. Its mixed polarities, apparent on September 18, were more obvious on the following day. The large leading member, R_{31}, was accompanied on the north, on September 18, by two companions, V_{11}, and V_{15}, and followed by a large spot, V_{20}. On September 19 the two northern companions had united within a single penumbra, the umbrae of which were recorded as V_{15} and R_{17} (Fig. 14, No. 1). On the following day this spot had fused with the large spot R_{33} to the south, leaving a single umbra, V_{16}, near the northern extremity of its penumbra (Fig. 14, No. 2), and this appearance persisted when the spot was nearing the west limb on September 26 (Fig. 14, No. 6). The development of the spot need not be described in detail, as it is sufficiently well shown by the cuts.

[1] *Mt. Wilson Contr.*, No. 165; *Astrophysical Journal*, **49**, 153–178, 1919, Fig. 2; Plate VII*a*, *b*, *c*; Plate VIII*a*, *b*, *c*, *d*.

One of the most remarkable spots we have ever observed was No. 1842, which appeared at the east limb on May 8, 1921, having formed since the previous rotation. On May 9 and 10 it was seen to consist of a very large irregular penumbra, containing a number of umbrae, of mixed polarity. The equator passed through the group, and on May 10 (Fig. 15, No. 1) Nicholson found that most of the points observed magnetically on the umbrae and various parts of the penumbra were *R* in the northern and *V* in the southern part of the group, corresponding with the polarities of the preceding spots of this cycle in the northern and southern hemispheres. On May 11 the group had split into preceding and following spots, each of which tended to be *R* in its northern and *V* in its southern parts, with the line of division near the equator, though there were some discrepancies (Fig. 15, No. 2). The *Hα*-spectroheliograms of this date showed eruptions in advance of the preceding spot, south of the small central spots, and both preceding and following the large following spot. Great activity continued in various eruptive regions in and about the group on subsequent days, and the division of each spot into two parts of opposite polarity also persisted, as illustrated in Figure 15, No. 3, from Nicholson's observations of May 15. A great terrestrial magnetic storm, accompanied by brilliant auroras, began suddenly on May 13, at $13^h\ 12^m$ G.M.T., when the leading spot was 5° east of the central meridian. The preceding edge of the bright calcium flocculi was on the meridian at this time, and the preceding bright *Hα*-flocculi had arrived there about twenty-four hours earlier. A more complete history of this remarkable group will be given elsewhere. Another interesting complex group, that of March 8, 1920, which was also accompanied by an aurora and terrestrial magnetic storm, is described by Nicholson in the *Publications of the Astronomical Society of the Pacific* for August, 1920.

MAGNETIC CLASSIFICATION OF 2174 SPOT GROUPS OBSERVED DURING THE PERIOD 1915–1925

In our previous paper we gave the magnetic classification of 970 spots observed during the period 1915–1917. Daily observations of all spots have been continued by Nicholson, Ellerman, Pettit,

Joy, Benioff, Hoge, and L. Humason, and these have been classified by Nicholson and Miss Mayberry, and checked in many cases by Hale. The results, which have appeared regularly since 1920 in the *Publications of the Astronomical Society of the Pacific*, are summarized in Table I, which, for convenience of comparison, also includes our previous results.

In Table I the classification is by groups, giving all groups equal weight and counting each separately on every successive return. As the same group is often classified as unipolar on some days and as bipolar on others, the average classification is given here. Thus the

TABLE I

MAGNETIC CLASSIFICATION OF 2174 SPOT GROUPS

Year	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified	Total
1915.....	17	33	9	38	51	9	8	3	14	182
1916.....	53	54	12	66	100	26	13	0	16	340
1917.....	45	85	15	88	134	38	15	2	28	450
1918.....	64	75	10	85	101	33	8	1	19	396
1919.....	52	54	11	47	77	22	9	3	21	296
1920.....	21	33	9	30	46	12	4	4	9	168
1921.....	11	34	5	26	28	8	2	1	25	140
1922.....	12	17	4	17	18	3	0	2	5	78
1923.....	1	7	2	5	16	2	0	0	4	37
1924.....	8	17	3	21	21	6	2	1	8	87
Total....	284	409	80	423	592	159	61	17	149	2174

successive columns give the number of groups classified under the respective heads for a majority of the days on which they were observed. There seems to be no change in the distribution of spot groups among these classes that can be associated with the changing phase of the $11\frac{1}{2}$-year cycle. This uniformity from year to year is best shown in Table II, where the percentages of the number of groups classified each year are given for each type. It should be noted that the numbers given in the "Unclassified" column are the percentages of all groups observed, while those in the other columns are the percentages of the groups actually classified.

The number of spot groups in each class was tabulated for the northern and southern hemispheres separately, and the percentage in each class was found to be the same north and south of the sun's

equator. Of the 2174 groups observed, 1149, or 52.9 per cent, were north of the equator. Of the total number of spot groups in each class given in Table I, 52.9 per cent might therefore have been expected in the northern hemisphere. The number calculated and observed in the northern hemisphere is as follows:

The slight excess of αp- and αf-groups in the southern hemisphere is so small that no physical significance is attached to it.

TABLE II

PERCENTAGE OF SPOT GROUPS IN EACH CLASS

Year	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified
1915.....	10	20	5	23	30	5	5	2	8
1916.....	16	17	4	20	31	8	4	0	5
1917.....	11	20	4	21	32	9	3	0	6
1918.....	17	20	3	22	27	9	2	0	5
1919.....	19	20	4	17	28	8	3	1	7
1920.....	13	21	6	19	29	7	3	2	5
1921.....	10	30	4	23	24	7	2	1	18
1922.....	17	23	5	23	25	4	0	3	6
1923.....	3	21	6	15	49	6	0	0	11
1924.....	9	21	4	27	27	8	2	2	9
1915–1924.....	14	20	4	21	29	8	3	1	7

TABLE III

Class	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified
Calculated.....	150	216	42	224	313	84	32	9	79
Observed.....	151	207	37	226	313	87	36	11	81

Table IV gives as percentages the frequency with which groups of each type were observed. These numbers give the mean number of groups of each type classified daily as a percentage of the total number of groups classified daily during the year. Daily observations of the magnetic fields of all spots were not made prior to January, 1917, so that these data are not available previous to that date.

A comparison of Table IV with Table II shows marked differences in three classes—αp, β, and Unclassified. The reason for the

increase from 7 per cent to 18 per cent for the total of unclassified spots is that in Table II only those spots are counted as unclassified for which no polarity observations were made. A group seen on several days may have been observed magnetically on only one or two days, because of adverse observing conditions. Its mean classification would then be given on the basis of those days for which magnetic observations were made.

The decreased percentage of β-groups and the increased percentage of αp-groups is due to the fact that the groups of long duration pass through the β-stage rather rapidly, while they exist as αp-groups

TABLE IV

FREQUENCY OF SPOT GROUPS OF EACH CLASS

Year	α	αp	αf	β	βp	βf	$\beta\gamma$	γ	Unclassified
1917.....	15	27	2	6	30	12	5	1	17
1918.....	18	26	3	14	26	9	2	1	16
1919.....	19	26	2	8	28	10	5	2	18
1920.....	11	32	4	12	29	7	2	2	16
1921.....	8	36	3	12	30	7	2	2	25
1922.....	17	24	5	19	24	6	1	5	26
1923.....	1	34	1	13	44	5	2	0	21
1924.....	6	30	4	19	28	8	4	1	18
1917–1924.....	15	28	3	11	29	10	3	1	18

for a much longer part of their life. The large groups usually begin as β- or βp-groups, but if the group is of the β-type at first it usually changes to βp after a few days. As the following spot breaks up and decreases, the group is βp until this spot has completely disappeared. The preceding spot may still be of considerable size, and may last for many days as an αp-group. Since Table IV is based on the frequency of groups in each class, the groups are essentially weighted according to their length of life. The groups of short duration often die out before the αp-stage is reached.

The fact that most groups begin as bipolar groups is shown in Table V, which is based on the magnetic classification of spot groups on the day of their formation. During the interval from 1917 to 1924 inclusive, 523 groups were observed on the first day of their lives. Groups observed for the first time are not counted in this

table unless observations on the day preceding the group's first appearance showed that no spots were visible in the region of the new group. Of the 523 groups mentioned above, only 426 were classified magnetically on the day of their formation. The numbers of groups thus classified which were observed on one, two, three, and on four or more days are shown in the last line of Table V under the column headings 1, 2, 3, and 4. The percentage distribution of these numbers among the various magnetic classes is shown in the columns above. The columns headed 5, 6, and 7 give similar data for groups which have lived more than five days, more than six days, and more than seven days, respectively, and thus present a segrega-

TABLE V

MAGNETIC CLASSIFICATION OF SPOT GROUPS AT FORMATION

Type	1	2	3	4	5	6	7	Total
α.....	32	12	9	12	13	13	10	18
αp.....	17	13	12	7	6	7	7	12
αf.....	10	5	3	3	2	3	0	6
β.....	23	26	34	37	39	39	39	30
βp.....	10	26	33	27	26	25	29	22
βf.....	7	15	7	13	13	12	13	11
$\beta\gamma$.....	0	3	0	1	1	1	2	1
γ.....	1	0	2	0	0	0	0	1
Total....	133	85	56	152	109	76	59	426

tion of the data in column 4. The last column gives the percentage in each magnetic class, irrespective of duration. The data included in columns 1, 2, and 3 usually cover the entire life of the groups in question, but many of the groups observed four or more days passed around the west limb, so that their total duration is unknown.

The most striking fact brought out by all of these tables is the large preponderance of bipolar groups, and the tendency of unipolar groups, even when not lapsing intermittently into the bipolar state, to hover continually on its margin. A study of the daily history of the spots further emphasizes this tendency, as it shows the frequent passage, back and forth, from one type to the other and the development from time to time of invisible spots in unipolar groups which never visibly attain the bipolar condition.

As Table II shows, 61 per cent of all classified groups were bipolar in character during the greater part of their existence, 24 per cent were ap or af, while only 14 per cent were a-spots. Another striking fact is the significance of preceding spots, which is shown by the large number of ap- and βp-groups, as compared, respectively, with those classified as af and βf.

THE LAW OF SUN-SPOT POLARITY

We are thus amply justified, when seeking the law of sun-spot polarity, in regarding bipolar groups as the dominant type. Unipolar spots followed by flocculi (ap) are treated as the preceding members

TABLE VI*

DISTRIBUTION OF MAGNETIC POLARITIES IN SPOT GROUPS (FIRST CYCLE)

First Cycle	Regular			Irregular				Mean Distance from Equator
	N. V_p-R_f	S. R_p-V_f	Total	N. R_p-V_f	S. V_p-R_f	Total	Percentage	
June, 1908–Jan., 1913..	7	17	24	0	1	1	4	9°

* The figures in these tables differ slightly from those given in our previous paper because a-spots were then classified with the preceding members of bipolar groups.

of incomplete bipolar groups, and those preceded by flocculi (af) as the following members of such groups. In the following tables our observations for the period 1908–1925, omitting symmetrical unipolar (a) groups, mixed bipolars ($\beta\gamma$), and complex groups, are assembled for three different spots cycles, the first including the few polarity observations made between June, 1908, and January, 1913 (Table VI); the second those of the full period, January, 1913, to October, 1924 (Table VII); and the third those from June, 1923, to January, 1925 (Table VIII).

In Table VI, representing a period when our attention was chiefly concentrated upon the verification and detailed study of the Zeeman effect in the few spots large enough for such work on the 6.7-inch solar image of the 60-foot tower telescope, the classification of polarities as "regular" or "irregular" is determined by the transmission of the red (R) or violet (V) n-component of λ 6173 by the "marked strip" of the compound quarter-wave plate when set

on the preceding spot. As the results show, the great majority of these spots gave the violet component (south-seeking or negative polarity) for the preceding spots of the northern hemisphere, and the red component (north-seeking or positive polarity) for the preceding spots of the southern hemisphere.

With the arrival of the high-latitude spots of the next (second) cycle, in December, 1912, we were surprised to find their polarity to be opposite to that of the spots of the first cycle. This is abundantly shown in Table VII, where the terms "regular" and "irregular" now apply to spots for which the preceding members give the red component (north-seeking or positive polarity) in the northern hemisphere, and the violet component (south-seeking or negative polarity) in the southern hemisphere. With only 2.4 per cent of exceptions, the reversal of polarities was thus complete.

TABLE VII

DISTRIBUTION OF MAGNETIC POLARITIES IN SPOT GROUPS (SECOND CYCLE)

SECOND CYCLE	REGULAR			IRREGULAR				MEAN DISTANCE FROM EQUATOR
	N. R_p–V_f	S. V_p–R_f	Total	N. V_p–R_f	S. R_p–V_f	Total	Percentage	
1913, 1914	18	13	31	1	1	2	6	22°
1915	61	60	121	1	0	1	1	19
1916	138	89	227	2	5	7	3	17
1917	188	175	363	4	3	7	2	15
1918	148	168	316	4	5	9	3	13
1919	96	122	218	0	2	2	1	12
1920	68	65	133	0	0	0	0	11
1921	54	45	99	1	2	3	3	10
1922	34	24	58	3	1	4	6	9
1923	12	5	17	0	0	0	0	7
1924	3	0	3	3	0	3	(50)	5
Jan., 1913–Oct., 1924.	820	766	1586	19	19	38	2.4	.....

This remarkable result led us to fear some systematic error, but scores of checks applied to our observations, which had been partly visual and partly photographic, invariably failed to shake their validity. We accordingly looked forward with the keenest anticipation to the appearance of the sporadic spots in high latitudes indicating the approach of the next cycle.

The first of these was detected by Ellerman on June 24, 1922,

a small a-spot at 31° N. latitude and 10° E. longitude, found to give the violet component, and thus to be of south or negative polarity. On the assumption that this was a regular preceding spot, a general reversal of polarities, corresponding to that observed in 1912, might be expected to occur at the minimum. As Table VIII[1] and Figure 16 indicate, this reversal has since taken place.

In studying the reversal of polarity at sun-spot minimum it is natural to inquire whether it is heralded by any progressive increase in the number of irregular spots or other suggestive phenomena.

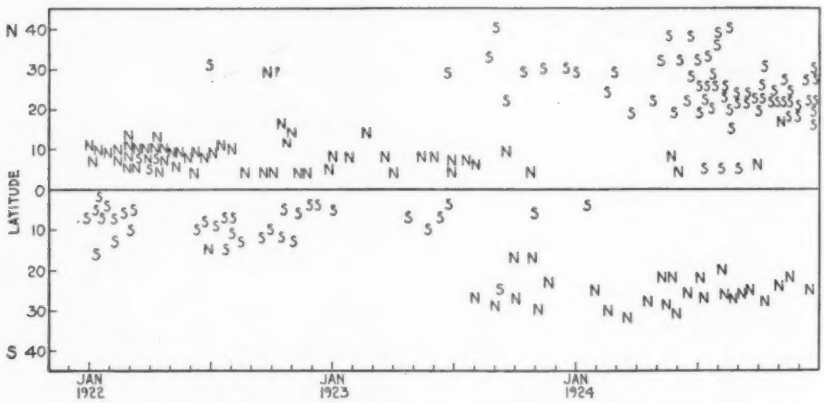


FIG. 16.—Heliocentric latitudes and magnetic polarities of sun-spot groups observed at Mount Wilson from January 1, 1922, to January 1, 1925. *N* (north-seeking) or *S* (south-seeking) represents the polarity of the preceding spot of each group.

As Table VII indicates, the percentage of irregular spots fluctuated from 0 to 6, but showed no progressive change. A test of the relative importance of preceding and following spots during various parts of the cycle can also be made by adding together all ap- and βp-spots, and comparing their number with the corresponding sum of the af- and βf-spots, as shown in Table IX.

The results afford no clue to the impending change of polarity at the minimum. The reversal of polarity is a sudden phenomenon, just as the advent of a new cycle of spots is abrupt, beginning in high latitudes before the spots of the old cycle have completely disappeared. Thus we find that at the time of sun-spot minimum four

[1] In this table "regular" and "irregular" have the same significance as in Table VI.

spot zones, characterized by distinct magnetic polarities, may coexist on the sun. During the interval June 1, 1922, to January 1, 1925, the maximum latitude of the spots of the last (second) cycle was 16°. The latitude of the present (third) cycle spots, of opposite polarity,

TABLE VIII

DISTRIBUTION OF MAGNETIC POLARITIES IN SPOT GROUPS (THIRD CYCLE)

THIRD CYCLE	REGULAR			IRREGULAR				MEAN DISTANCE FROM EQUATOR
	N. V_p–R_f	S. R_p–V_f	Total	N. R_p–V_f	S. V_p–R_f	Total	Percentage	
1923.....	8	7	15	0	1	1	7	27°
1924.....	51	18	69	1	0	1	1	25
June, 1923–Jan., 1925..	59	25	84	1	1	2	2	.....

has ranged from 40° to 16°. The boundaries of these zones are not sharply defined, and in a few cases it is doubtful to which cycle the group belongs. Thus group No. 2033, which appeared on September 8, 1923, in latitude 25° S., had polarities like those of the second cycle,

TABLE IX

Year	$\alpha p+\beta p$	$\alpha f+\beta f$
1917.....	57	14
1918.....	52	12
1919.....	54	12
1920.....	61	11
1921.....	66	10
1922.....	48	11
1923.....	78	6
1924.....	58	12

but because of its distance from the equator it has been considered as a spot of the third cycle with irregular polarity. A still more difficult case is No. 2079, which first appeared on July 9 in latitude 5° N. Its polarities were like those of the third cycle, but its low latitude puts it with the spots of the second cycle, as is shown in Figure 16. It has been included in Table VII, and since it was observed at two returns, as Nos. 2085 and 2094, with the same irregular polarity, it alone accounts for the irregular second-cycle

groups of 1924. On its next return, as No. 2101, its polarity had changed, making it a regular group of the second cycle.[1]

The temporary existence in each hemisphere of two zones, in which the great majority of the spots are of opposite polarity, is a most striking phenomenon, which cannot fail to be of significance in its bearing on the solar constitution.

Mention should be made of the sharpness with which the equator separates spots of opposite polarity, as illustrated in Figure 17. Two bipolar groups appeared at the east limb of the sun on August 12, 1919, one 6° N., the other 3° S. During their passage across the disk the leader of the northern group moved toward the equator at the rate of 4500 miles per day, while the preceding spot of the southern group rapidly increased in diameter. By August 23 the edges of both these spots touched the equator. On their return to the east limb on September 10 the following spots of both groups had disappeared, leaving only the leaders, which remained in the same relative positions until they began to break up on September 15. Figure 17 shows them as they appeared on September 13, when the northern spot was 30,000 miles in diameter, the southern one 26,000 miles in diameter, and the distance between their centers 33,000 miles. At this time their respective maximum field-strengths were 3400 and 2900 gausses, of opposite polarity.[2] Scores of similar instances could be given, showing the almost unerring tendency of a group to exhibit the polarity characteristic of its hemisphere, even if it be within a degree or two of the equator, or actually in touch with it.[3]

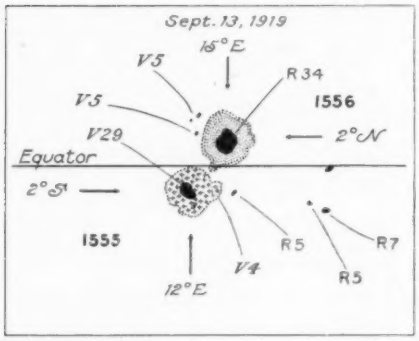


FIG. 17.—Spots of opposite polarity near the equator. Groups Nos. 1555 and 1556, September 13, 1919.

[1] "Summary of the Mount Wilson Observations of Sun-Spots for September and October, 1924," *Publications of the Astronomical Society of the Pacific*, **36**, 355, 1924.

[2] Nicholson, "Two Sun-Spots Close to the Sun's Equator," *ibid.*, **31**, 277, 1919.

[3] Rarely, as in the complex group No. 1842 (Fig. 15), the polarities do not correspond exactly with their respective hemispheres.

The polarity law, which represents all of our observations with only 41 exceptions out of 1735 groups, is best expressed graphically (Figs. 18 and 19), but may also be stated as follows:

The sun-spots of a new $11\frac{1}{2}$-year cycle, which appear in high altitudes after a minimum of solar activity, are of opposite magnetic polarity in the northern and southern hemispheres. As the cycle progresses the mean latitude of the spots in each hemisphere steadily decreases, but their polarity remains unchanged. The high-latitude spots of the next $11\frac{1}{2}$-year cycle, which begin to develop more than a year before the last low-latitude spots of the

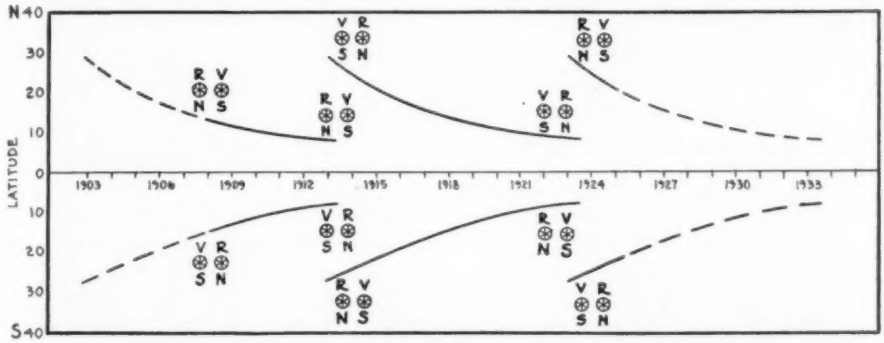


FIG. 18.—The law of sun-spot polarity. The curves represent the approximate variation in mean latitude and the corresponding magnetic polarities of spot groups observed at Mount Wilson from June 1908 to January 1925. The preceding spot is shown on the right.

preceding cycle have ceased to appear, are of opposite magnetic polarity.

It can hardly be doubted that this law will apply in future cycles, involving a complete reversal of polarities at each successive minimum. Thus while the $11\frac{1}{2}$-year interval correctly represents the periodic variation in the number or total area of sun-spots, the full sun-spot period, corresponding to the interval between the successive appearances in high latitudes of spots of the same magnetic polarity, is twice as long.

This 23-year interval may be called the magnetic sun-spot period, to distinguish it clearly from the familiar $11\frac{1}{2}$-year frequency period. The sun-spot numbers or areas might be expected, however, to show some evidence of a 23-year period, and this was actually detected by Professor Turner in 1913 from a careful analysis of the

Wolf numbers. In the *Monthly Notices* for November, 1913, he remarks: "Now in the first place we find that there is not a satisfactorily uniform period of $11\frac{1}{2}$-years, but rather a double period of 23 years, the halves of which are not quite symmetrical." In a recent paper,[1] describing a harmonic analysis of the Greenwich north and south mean latitudes and the logarithms of the north

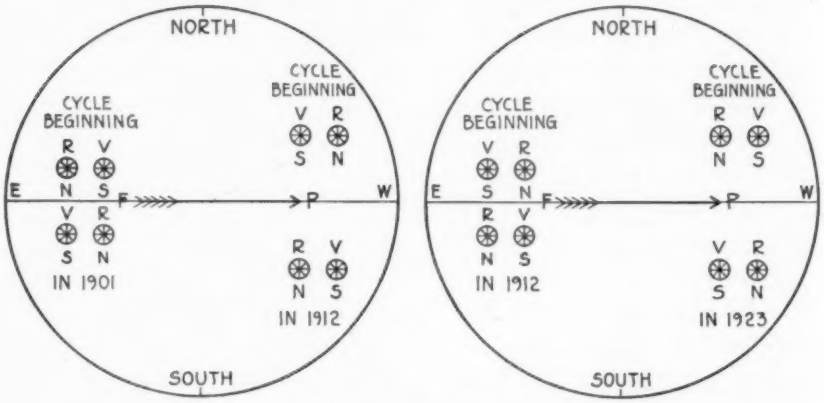


FIG. 19.—Sun-spot zones during the minimum of solar activity. Two zones in each hemisphere, in which the spots are of opposite magnetic polarity, exist for about two years at the time of each sun-spot minimum.

and south spotted areas, he confirms the earlier result and adds the following important conclusions:

The "even" cycles 1888–99 and 1912–23 differ from the "odd" cycles 1876–87 and 1900–11 as follows:

a) The spots are in the mean 1° further from the equator in both hemispheres, and the spotted area larger in the ratio of 143 to 126.

b) The phases of the variation are earlier by about 5.2 months, both as regards latitude and area; the ranges are also slightly greater.

c) The latitudes indicate a mean period of 11.35 years and the areas a mean period of 11.65 years, the mean being closely 11.50 years, for the 48 years analyzed.

It is to be hoped that solar investigators will look for other possible differences in the behavior of the spots of successive $11\frac{1}{2}$-year cycles.

MOUNT WILSON OBSERVATORY
June 1925

[1] *Monthly Notices*, **85**, 467, 1925.

REVIEWS

Tabelle der Schwingungszahlen der auf das Vakuum reduzierten Wellenlängen zwischen λ 2000 A und λ 10000 A. By H. KAYSER. Leipzig: S. Hirzel, 1925. Pp. v+106. 4to. Cloth, 13 gold Marks.

It is well known that true regularities in spectra are accurately and simply expressed only when the spectral lines are represented by their frequencies or wave-numbers in vacuum. In fact, the combination principle appears to be strictly true for these data, and differences of constant wave-number are therefore important indications of term combinations in spectra.

The search for regularities among line and band spectra has been successful beyond all expectations during recent years. These investigations, especially in cases of complex spectra each comprising several thousand lines, have involved a vast amount of labor in converting the observed data as to wave-length into usable form. The usual procedure has been to apply to each wave-length as observed in standard air its appropriate correction for conversion to its value in vacuum and then, with the aid either of calculating machines or reciprocal tables, to compute seven or eight significant figures of its reciprocal. For many results, it has been fairly convenient to use the table of reciprocals by Oakes, or preferably that by Cotsworth, but in either case the eighth place was inaccessible and the correction to vacuum remained a separate operation.

In order to save much of the time and trouble of a large and constantly increasing number of investigators, Professor Kayser has dedicated some of what he calls the "spare time of his old days" to the preparation of a table from which eight-place wave-numbers in vacuum corresponding to wave-lengths in standard air are directly and easily obtained. The material is arranged like that of a logarithm table; between 2000 A and 7000 A the interval is 0.1 A, while from 7000 A to 10000 A it is 1.0 A. The table proper is based on two additional columns of data determined from the dispersion formula of Meggers and Peters for air at 15° C. and 760-mm *Hg* pressure. The first of these extra columns contains refractivities, computed with the aid of logarithms, for each angstrom unit except above 7000 A where intervals of 10 A suffice; and the second contains the product of refractivity and wave-length, that is, the correction required by

the latter to convert it to its value in vacuum. Vacuum wave-lengths were obtained for each 1/10 interval by linear interpolation, and the reciprocals of these values were then computed by machine, the seventh place being strictly correct, the eighth possibly containing errors of 1–3 units.

From one week of experience with this table, I estimate that it will eliminate two-thirds of the drudgery from that branch of spectroscopy which it is intended to benefit. Every investigator in this field will be grateful to Professor Kayser for thus rendering another great service to the science to which he has already devoted the best part of his life.

W. F. MEGGERS

Modern Astrophysics. By HERBERT DINGLE. New York: The Macmillan Company, 1924. Pp. xxviii+412. Pls. 46; figs. 33. $8.50.

If it be accepted that the works of Scheiner and Miss Clerke, under the titles, *Astronomical Spectroscopy*, and *Problems in Astrophysics*, have set standards of treatment in the field of astrophysics, it may be expressive to say that Dingle's book conforms more closely to the latter. The style is fresh, vigorous, and frequently epigrammatic, but not too ornate. The announced intent is to appeal to popular readers; and to that end technical and unfamiliar language is not used without explanation, while mathematical formulae are relegated to the footnotes. Though its pages are not many, the book is sufficiently comprehensive to be of use, as a review of the position of a year ago, to the practical astrophysicist. Whether or not it is the part of the reviewer to protect those who are victims of the dangerous habit of reading books, it should be said that this new volume merits perusal by all who are interested in astrophysics.

In a popular work the natural tendency is to feature the spectacular, sometimes at the expense of the fundamental. In the present case the author has chosen his material wisely, has arranged it consistently, and discussed it with notable ingenuity. The actual authorial effort per page runs very creditably high.

Limited space is as troublesome in the printed page as is unlimited space in theories of cosmogony. Space restrictions undoubtedly account for the lack of historical background, so striking even in a book on modern astrophysics. It is disconcerting not to find in the text any mention of the three great pioneers, Huggins, Vogel, and Keeler, who laid foundations in stellar spectroscopy; or to encounter personal references in connection with the fission theory of double star genesis without the names

of Darwin and Poincaré. Could not historical references displace profitably rhetorical introductions and conclusions of some of the chapters of the work?

Restriction of space must be accountable again for scant allusion to instrumental and observing technique, or even for a curtailed list of astrophysical instruments, leaving a void that the popular reader will not realize and therefore will not feel. In the same way the expected discussion of the classical problems of such objects as *Beta Lyrae, P Cygni* and the like will be looked for in vain. It was of course wise to restrict the scope of the volume rather than to cover a wider range inadequately. Suffice it to say that a place will remain in the astronomer's book-shelf for the fuller work which the author mentions in his preface. It is reassuring to know that plans are afoot both in England and Germany to provide the needed volume.

The present volume is divided into four parts. In the first, the principles of spectroscopy are explained in so far as they can be applied to the heavenly bodies. In the second part, the various physical features of the stars are dealt with, considering each property in relation to the spectral types. The conclusions that have been drawn from these considerations with regard to stellar evolution and the distribution of the stars are then presented. The discussion of stellar movements and velocities fills the longest chapter in this section. In the third part, the more detailed characteristics of the different types of celestial objects are passed in review. This is the most extensive section of the book. It includes a thirty-seven page discussion of the sun. In the fourth part, the structure, history, and destiny of the universe are considered in the light of known facts. Preceding the main body of the text there is an introduction of twenty-eight pages, designed to prepare the popular reader's mind for the volume before him. Here the problem of astrophysics is stated as that of the distribution of matter and energy in time and space.

It is not easy to pick out any section of the last three of the book that stands out conspicuously from the rest. Perhaps the author's own ideas are more prominent in the last three chapters, on cosmology. Here the galactic theories of Kapteyn and Shapley are strikingly brought together with the conclusion that there is no sign at present of a blending of the two. The problem of the spiral nebulae is, of course, left unsolved with the final pronouncement that ". . . . the crux of the spiral nebula problem lies in the question of dimensions of the galactic system and the distances of the spirals." Other questions considered in this section are the evolution of the galactic system and the possible cycle of material devel-

opment. These gropings in the dim vistas of cosmology lead to no commanding summits. They do blaze a path which may be followed again with economy of time and effort. Through it all the reader feels a striving impulse to brighten the author's road in the light of the recent results of Eddington, Hubble, and others.

The figures and plates in the volume are well selected and appear to advantage. Modern illustrations are substituted for the old conventional figures. By a strange trick of chance two important spectra in the reproductions of the Harvard sequence in Plate XIII*c* turned out badly. The reviewer is glad to note that the sequence G-R-N of stellar spectra which he prepared for publication is reproduced successfully in Plate XIV*b*.

For a first edition the book is remarkably free from errors. Some which do occur are typographical as, for instance, when it is stated (p. 68) that *Hα* particularly appears bright in division Md (see correct statement on page 264), or when the date of the 1900 solar eclipse is given as May 25, on Plate XXIX. In places the attempt to reach the layman's plane may lead to statements such as (p. xx) "The stars and nebulae, and the Milky Way, are far too distant from us for the telescope to magnify them sensibly," or (p. 92) "The proper motion is the angle subtended by the star's path at the Sun . . . . ," or (p. 244), referring to the maxima of Algol's light curve, "The lines *cd* and *fg* are not horizontal. . . . . This . . . . shows that the components of the star are not spherical, but ellipsoidal, ... ," or (p. 241) "the axis of rotation is parallel to the edge of the page." As it is noted on page 68 that Class R spectra have been described as O spectra reversed, it is hoped that the reader will not miss the discussion of this point on page 292. To facilitate the task of the historian it ought to be said that the work on Class R and N stars at the Detroit Observatory should be credited jointly to W. C. Rufus and R. H. Curtiss and not to the latter alone as on page 291.

The manuscript of the volume was originally completed in May, 1923, but insertions were made to bring the treatment up to May, 1924. It was not practicable, however, to incorporate the findings of Eddington on the relations between the masses and luminosities of the stars. It is impressive to note how the discussions of stellar and material evolution and the problems of the spiral nebulae might have been modified had they been written two years later. But *Modern Astrophysics* presents a faithful cross-section of knowledge, thought, and opinion as they existed early in 1924 and as such is a valuable addition to our scant list of books in this field.

RALPH H. CURTISS

Meteors. By CHARLES P. OLIVIER. Baltimore: Williams & Wilkins Co., 1925. Pp. xix+276. 8vo. 23 plates.

This is a book for the professional astronomer rather than for the general reader. While it contains elementary matter, simply stated, there is a constant recourse to technical concepts and technical terms, notably those of orbital motion, that must prove embarrassing to the layman; and even the more instructed reader will at times regret that the labor of perusal has not been mitigated by greater precision and clarity of statement. A misspelled word, an erroneous figure, even an impossible formula (p. 177) may be condoned as "printers' errors" but with increasing frequency of occurrence they suggest an undue measure of haste in the author's work. In the present case this suggestion is strengthened by an apparent vacillation between a reformed spelling and the more conventional orthography, e.g., siderial, exterpolate, many times repeated but with occasional lapse to more common forms.

But these are minor matters, blemishes upon an otherwise excellent work in which the results reached by many astronomers are collated, interpreted, and criticized by one whose own research and independent judgment are here in evidence. Within reasonable limits of space no such digest of material can be complete and it is the author's privilege to determine what shall be ignored. Nevertheless, the reviewer notes with regret the slight attention paid to the internal structure of meteorites and the absence of all reference to H. A. Newton's ingenious graphical methods for discussing the motion of meteorites.

The subject matter of the text is primarily meteor swarms, the sporadic meteor being given little heed. After a brief historical introduction and a chapter upon methods of observation, the author introduces in successive chapters, comets, the Leonids, Perseids, Lyrids, Bielids, and the swarms attendant upon the Halley and Pons-Winnecke comets. The treatment of these is in the main historical, illustrating the growth of knowledge concerning these particular aggregates. There follows, in several chapters, an extended discussion of radiants with particular reference to stationary radiants, concerning whose existence the author is something more than skeptical. Other chapters are devoted to exposition of the mathematical problems arising from observation of meteors, determination of their height, velocity, motion, and origin, i.e., their history prior to encountering the earth. The possible effect of meteors upon earth and moon is briefly considered and a final chapter of eight pages summarizes the author's conclusions, some of which are noted below. The book's attractiveness is enhanced by some two dozen full-page illustra-

tions, many of which, however, seem only distantly related to the text, e.g., pictures of nebulae, star clusters, and the Milky Way.

Quite naturally the author's interpretation of meteors and meteoric phenomena is largely determined by his views of cosmogony. Upon the whole he inclines to the planetesimal theory and with reference to it holds to a series of catastrophes as the necessary antecedent of meteors. The genesis of the solar system is one such catastrophe, but others seem to be required by the well authenticated cases of meteors whose hyperbolic velocities indicate that they have come from "stellar systems enough similar to our sun to generate similar bodies."

With its abundant reference to the literature regarding meteors this book will serve an important function as a work of reference, but equally it should serve as an incentive to younger astronomers to take up the work and extend the results of their predecessors. The author's temperament and style, at its best, appear well adapted to this end and his book may be heartily commended to the student as in substance a sound work if not an exhaustive one.

GEORGE C. COMSTOCK

Die veränderlichen Sterne. Zweiter Band: Mathematisch-Physikalischer Teil. Von DR. JOHANN STEIN, S.J. Freiburg: Herdersche Verlagsbuchhandlung, 1924. 4to. Pp. xx+383.

The first volume of the work on variable stars by Father J. G. Hagen was reviewed in this *Journal*, **40**, 483, 1914, and **60**, 140, 1924, by Professor J. A. Parkhurst. The second volume by Father J. Stein on the mathematical-physical theories of variable stars is a fitting companion in this elaborate undertaking. It is more than a dozen years since the reviewer had the privilege of visiting Father Stein and of seeing part of the manuscript of the projected work, and now after the war it has finally become possible to print it on the original plan. As stated in the Introduction, the author's purpose is to give a survey of the many theories which have been proposed to explain physically the different light changes of variable stars, the literature of which is widely scattered in a variety of publications. It is a great convenience to have brought together the various theories, often revised or corrected, and put in a form more easily studied than the original. Some of the theories are summarily dismissed as wrong or unimportant; but, as someone has said, it is well to keep all theories in reserve and be ready to find some application of almost any suggestion for the cause of stellar variation.

The work is divided into four main parts, under the headings: New Stars, Long-period Stars, "Blinksterne" (for which there is no good equivalent in English), and Eclipsing Variables. This classification of variables seems ample for the purpose, and until we have satisfactory explanations for the regularly periodic stars, there is little need of worrying about the proper assignment of irregular variables. Under "Blinksterne" are included stars of the δ-Cephei and cluster type. Both Hagen and Stein seem scrupulously to avoid the term "Cepheid" variable, in which prejudice they have the approval of the reviewer.

The theories of novae are of course largely speculative, and after reviewing some of the early suggestions, the author gives in detail the theory of Seeliger which attributes the outburst to a star colliding with a nebula or dust cloud. The evidence given on the changes of spectrum is practically limited to the cases of Nova Aurigae 1892, and Nova Persei 1901, and furnishes the reader with a beginning which he will have to continue elsewhere in the spectroscopic studies of novae during the past quarter of a century. A whole chapter is given to the rapidly moving nebulosity about Nova Persei 1901, and the explanation that this motion is due to the successive illumination of dark material by the light from the original outburst as it traveled outward.

Under stars of long period are two main classes of theories, the first based upon the rotation of a non-uniform luminous body, and the second upon the periodic changes of spots similar to those on the sun. Studies of the spectra of Mira Ceti and others of this class are discussed, and it is interesting to note that many of the ideas concerning the spectral changes have since been upset by the recent discovery at the Mount Wilson and Lick Observatories that after all Mira is a double star, and that the companion is responsible for some of the peculiarities when the light of the main star is faded out at minimum.

Under "Blinksterne" are given a number of older theories, some obviously untenable, and then the foundation of the newer theories based upon the relation between the light-curves and velocity-curves—the latter term denoting impartially the changes in the spectra. Both the pulsational and binary explanations of these variables are given, with some of the difficulties of each. In accordance with his resolution not to discuss purely statistical theories of variables which are not upon any physical basis, Father Stein gives little prominence to the period-luminosity law of variation which has been used by Shapley with such far-reaching results in determining stellar distances.

It is a relief to turn from the uncertainties of the novae, long-period,

and δ-Cephei variables, to the clear cases of geometrical occultation of the eclipsing stars. Here the agreement with observation becomes strikingly good without stretching theory beyond all plausibility. The derivation of the elements of an eclipsing system from the light-curve of a star like Algol began with E. C. Pickering in 1880, who was followed in 1889 by Harting, a student of Seeliger, and the method has since been generalized to include the effect of ellipsoidal figure, reflection of light, etc., all of which the present work gives in detail. After most of these chapters were written, there appeared the papers of Russell and Shapley, whose work placed the theory of eclipsing systems upon a more practical basis. Their method is given at length, including the necessary tables which are printed in full.

The work concludes with a discussion of a score or more eclipsing systems, including a special chapter each on our old friends Algol and β Lyrae. Vogel's spectrographic determination of the variable radial velocity of Algol gave the first convincing proof that such a close binary system is possible, but some day we shall hope to see a reference to Vogel's classical work without the quotation of the familiar figures of 4/9 and 2/9 for the masses of the components in terms of the sun. These figures were derived from a merely approximate light-curve, and on the erroneous assumptions of a wholly dark companion and that the two bodies are of the same density.

It is difficult to exaggerate the service that Father Stein has rendered all students of variable stars in bringing the various theories together for easy comparison and study. The historical part seems to be accurate and complete, and one need not go to the original articles to see just what may have been of value in some of the discarded theories. The work can scarcely be recommended to the layman for light reading, and there is little need of an English translation, as a student with the mathematical training necessary to follow the work will no doubt be able to read scientific German.

The press work and paper are of excellent pre-war quality, and there are relatively few misprints in those parts which the reviewer has read in detail. This second volume may be secured for about ten dollars, unbound, from the B. Herder Book Company, St. Louis.

JOEL STEBBINS